Journal of the Royal Society of Western Australia, 89: 129–154, 2006

Holocene palynology of five wetland basins in the Becher Point area, southwestern Australia

C A Semeniuk[1], L A Milne[2], V Semeniuk[1] & P G Ladd[3]

[1] V & C Semeniuk Research Group,
21 Glenmere Rd., Warwick, W.A., 6024
[2] Center for Forensic Science, The University of Western Australia,
Crawley, W.A., 6009
✉ lamilne@cyllene.uwa.edu.au
[3] School of Environmental Sciences, Murdoch University,
Murdoch, W.A., 6150
✉ p.ladd@murdoch.edu.au

Manuscript received June 2006; accepted September 2006

Abstract

The wetlands on the Becher Cuspate Foreland provide an opportunity to undertake palynological studies in a series of discrete small basins all belonging to the same wetland suite – the Becher Suite – from middle to late Holocene. The wetlands have formed progressively as the beachridge plain prograded westwards, and provide a landscape within a temporal framework wherein wetland initiation ranges from *circa* 4500 years in eastern locations to *circa* 900 years in western locations. Using patterns of surface pollen composition in relation to extant vegetation as a baseline the middle to late Holocene record was investigated in five wetlands, selected to incorporate different ages and plant/vegetation assemblages. The five wetland basins, in relatively close proximity and in the same climatic setting, have markedly different pollen history reflecting intra-basinal evolution. Pollen content of the sediment to shallow depth suggests that the following vegetation assemblages will be useful to interpret past vegetation patterns: *Centella asiatica* (L.) Urb. herb assemblage, *Baumea articulata* (R. Br.) S. T. Blake sedge assemblage, *Typha* (L.) sp. sedge assemblage, mixed *B. articulata* and *Typha* sp. sedge assemblage, *Melaleuca teretifolia* Endl. scrub assemblage, *M. rhaphiophylla* Schauer forest/shrub assemblage, with understorey of *C. asiatica, M. viminea* Lindley heath assemblage, *M. cuticularis* Labill. assemblage, and wetland margin of *Xanthorrhoea preissii* Endl., *Isolepis nodosa* (Rottb.) R. Br. and *Sporobolus virginicus* (L.) Kunth assemblages.

Radiometric dating of the sediment cores was used to provide an age structure. Pollen diversity and abundance against this age structure indicated that, except for *X. preissii* and *I. nodosa*, most wetland species were present over the interval of 4500 years BP to the present in the middle to late Holocene. However, there were a number of other important patterns in the down profile abundance of wetland pollen taxa and their inter-basin variation at isochronous levels: a lack of continuity down profile for some species; fluctuations in numbers of pollen taxa that were continuous; lack of correlation in timing of the peak pollen numbers between separate basins; variable total composition at the same isochron level from wetland to wetland; variable total composition of wetland pollen at different ages within the same wetland; the association of pollen species with sediment types; increases and decreases of wetland margin pollen taxa in the down profile composition; and the recent appearance of *I. nodosa* and *X. preissii* within the last *circa* 1500 years. The patterns of pollen derived from wetland vegetation in individual wetlands suggest that the ancestral distribution and abundance of plant assemblages in the Becher wetlands was a function of intra-basin environmental changes caused by wetland evolution. In contrast, pollen derived from upland vegetation exhibited continuity down profile, suggesting that delivery of upland pollen has been largely consistent, though variable in abundance and composition from basin to basin, and being exogenic, it has not reflected (hydrochemical, edaphic or hydroperiod) environmental conditions within the wetlands.

The combination of slow rates of sedimentation and bioturbation have obliterated any potential fine scale sequencing of pollen, resulting in a pollen record which may contain a composite of up to several hundred years of mixed wet and dry climate assemblages, making it difficult to interpret detailed climate history. However, the appearance of *X. preissii* and *I. nodosa circa* 1500 years ago, coupled with a corresponding change in stratigraphy, probably signals a recent increase in rainfall.

Keywords: palynology, Holocene, wetlands, Becher Point, south western Australia

© Royal Society of Western Australia 2006

Introduction

The wetlands in the Becher Suite in southwestern Australia provide an opportunity to study the pollen record in Holocene basins using an approach unprecedented in Western Australia. The wetlands have developed on the Holocene Becher Cuspate Foreland (Searle *et al* 1988; C A Semeniuk 2006; and Fig. 1), and occur in inter-dune depressions or swales of this beachridge plain. As described by Searle *et al* (1988), the cuspate foreland consists of a series of parallel beachridges, which range in age in the region from *circa* 7000 years at its eastern part, progressively younging westwards to contemporary at its shore. In the Becher Point area, the age of the cuspate foreland ranges from *circa* 5000 years at its eastern part to contemporary at its shore. In response to the progradation of the coast westwards, there was a general and progressive development of inter-dunal (swale) wetlands on the beachridge landscape (C A Semeniuk 2006). Thus, formation of the Becher Suite wetlands on this westward-younging prograding coastal plain commenced *circa* 4500 years in eastern and older parts of the beachridge plain of the Becher Cuspate Foreland and have continued to form up to *circa* 680 years in the western younger parts.

In general, elsewhere on the Swan Coastal Plain, wetlands in a Pleistocene landscape (of Pleistocene quartz sand dunes and lithified calcareous coastal dunes; *cf* Semeniuk & Glassford 1989) have developed as the post-glacial rising sea level resulted in regionally rising ground water tables across the ancestral (precedent) Swan Coastal Plain. As rising water table levels stabilised to present positions, lowlands and depressions in the landscape close in elevation to the present water table became inundated or waterlogged, and wetlands came into existence, filling with peat, diatomite and calcilutite (Semeniuk & Semeniuk 2004; 2006). Essentially, most of these wetlands came into existence at around the same time, co-incident with the stabilisation of a rising sea-level, and stabilisation of a rising regional ground water table. The wetlands of the Becher Suite provide a contrast to this pattern in that they have come into existence as the landscape developed by progradation. As such, the array of younging landforms, and younging wetland basins on the cuspate foreland provide an opportunity to study the comparative palynology of wetland basins in the same setting and suite initiated at different times during the Holocene. The basins in their near-contemporary setting are in close proximity and thus provide indication of how diverse the palynological record can be at the local scale. The wetlands also are reasonably well documented in terms of stratigraphy, hydrochemistry, and age structure and hence provide indications of how the palynological record reflects sedimentary, hydrochemical and ecological history.

The approach of this study is somewhat different from most palynological studies, in that there is a focus on several wetland basins in a comparative manner locally, rather than using one wetland to characterise the region. The main objective of the study was to construct the history of vegetation in five selected wetlands that have a range of ages but a similarity of sedimentary fill. The data in this paper, together with the results of C A Semeniuk (2006) and C A Semeniuk *et al* (2006), can be used to determine whether climate or intra-basinal evolution explains changes in wetlands and their vegetation through time.

Study sites, materials and methods

Five age-graded wetlands were selected for detailed stratigraphic and palynological examination to investigate the pollen record over the middle to late Holocene on the Becher Cuspate Foreland, *viz.* wetlands notated as 161, 162, 163, 135, and 9–14 (Fig. 1). All the wetland basins are relatively small and oval, *i.e.*, generally < 50 m x 100 m. The bases for their selection are outlined below.

Wetlands 161, 162, 163 are located on the *circa* 4500 year isochron of the beachridge plain of the Becher Cuspate Foreland (Fig. 1), and represent three adjacent wetland basins, which differ in terms of their time of initiation and their history of filling. Wetland 161 was selected as it is the oldest wetland in the study with the greatest thickness of (accretionary) wetland fill, while 162 and 163 were selected because they lie adjacent to 161 and each wetland is colonised by different assemblages of plants. Wetland 135 was selected because it is situated on the 3000 year isochron of the beachridge plain, representing a middle age wetland basin; it has sufficient thickness of wetland fill, and is currently colonised by a plant assemblage not represented in the other wetlands. Wetland 9–14 was selected because it is situated on the 1500 year isochron of the beachridge plain, and represents one of the youngest of the wetland basins in the region; it has sufficient thickness of fill, and supports a single plant assemblage. Although all wetland basins have sedimentary fill of calcilutite, the progressive filling of the basins with sediment has resulted in different thickness and, consequently, varying hydrological and hydrochemical history. These factors have effected the serial evolution of the vegetation.

The centre of each of the selected wetlands was cored using a 10 cm diameter PVC tube to extract an intact core. The cores penetrated to a depth to intersect the basement Safety Bay Sand that underlies the wetland sedimentary fill. The cores were frozen within an hour of their retrieval and stored in a freezer at -30° C until ready for processing. Later, the cores were split longitudinally, photographed, and subsampled. One half of the core was sampled for pollen, and for sediment for ^{14}C analysis. Small samples of sediment were extracted for palynological processing from the core using a 1 cm diameter micro-corer at the sedimentary surface, then at 3–5 cm depth, and thereafter at 10 cm intervals. To provide an age structure for the pollen, *circa* 20 grams of carbonate mud was taken from selected depths and prepared for ^{14}C analysis (Fig. 2). This mud sample was wet-sieved through a 63 μm mesh to eliminate any sand grains (these potentially may be earlier Holocene, or even Pleistocene grains), and to separate all mud fractions from biogenic, or exogenic sand and rootlet material > 63 μm. The sieved mud was collected in a large clean container. Because it was important that only Holocene wetland biogenic carbonate mud was used for radiocarbon analyses, slurried samples of the mud after the first sieving were re-sieved through the 63 μm mesh.

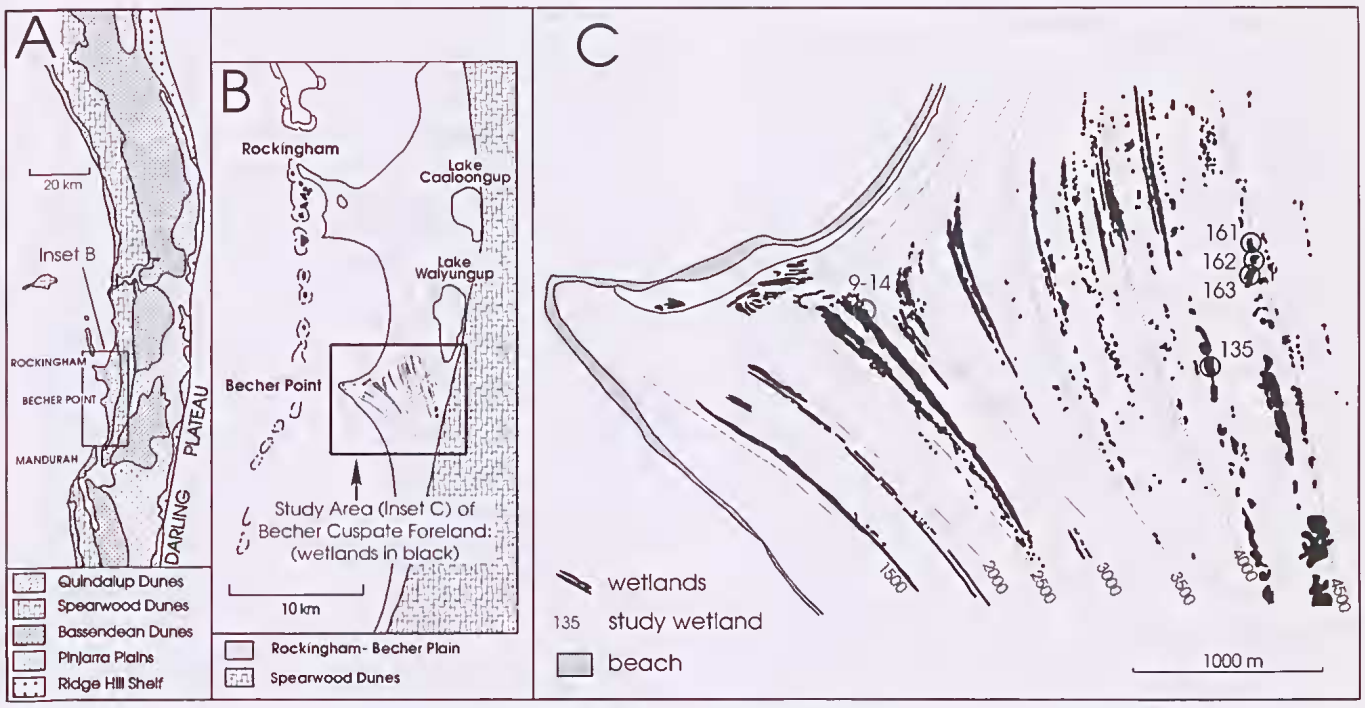


Figure 1. A. Location of Study Area in southwestern Australia. B. The Becher Point area and the Cuspate Foreland. C. Wetlands of the Becher Point area. Basins selected for study are circled and annotated; also showing isochrons in ^{14}C years (after Searle *et al.* 1988).

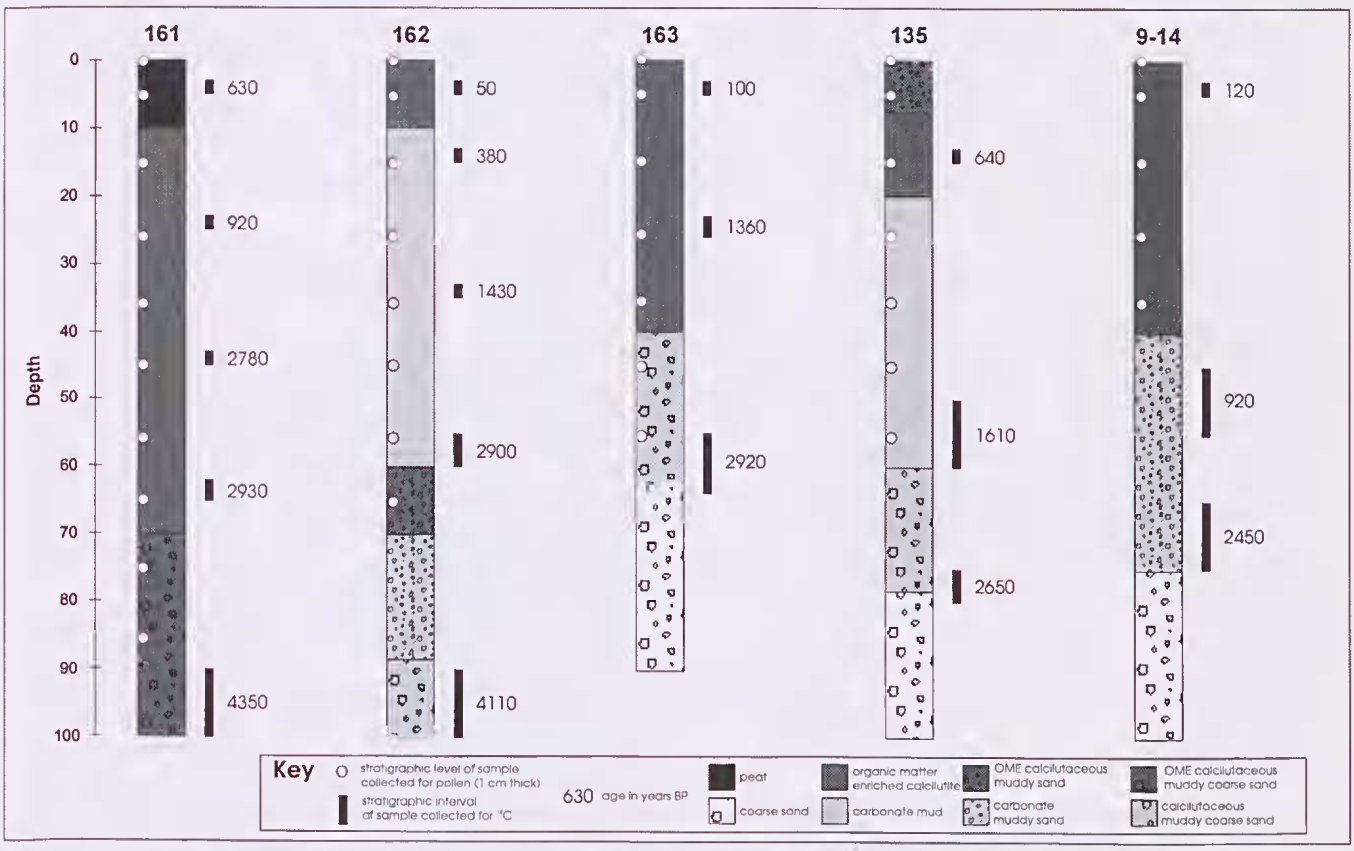


Figure 2. The stratigraphy of the centre of each of the wetland basins selected for study; also showing sampling points for pollen and samples collected for radiocarbon analyses. Sediment terms after Semeniuk & Semeniuk (2004). OME = organic matter enriched.

This second-stage sieved sample was then oven-dried in clean glass containers, and the base of the dried mud cake was examined with a stereoscopic microscope to ensure that there were no sand grains that could have preferentially settled to the base of the slurry. The dried sand-free mud was weighed to ensure that it conformed to the minimum required weight (18–20 g) for ^{14}C analysis. Samples were processed for ^{14}C at the CSIRO laboratories in Adelaide, South Australia, where they were acid-digested to collect CO_2 for the analysis using a

method for direct absorption of CO_2 for radiometric counting. A separate ^{13}C analysis of CO_2 was also undertaken for all samples.

Methods of pollen extraction and techniques of analysis are described in C A Semeniuk *et al.*, 2006. Sediment samples were processed to extract the organic material following the general procedures of Erdtman (1960), Phipps & Playford (1984) and Nilsson & Praglowski (1992). To determine the abundance of indigenous pollen species in each sample relative to a standard sediment volume, 1 cm^3 of each sediment sample was spiked with a known quantity of an alien pollen species (Betulaceae) prior to processing. Generally, a two hundred grain pollen count was conducted for each sample. Pollen identification was referred to modern pollen standards, referenced to publications, or assigned to an uncategorised group.

Pollen taxa identified by microscope were later assigned to the following groups:

1. wetland pollen;
2. upland pollen (*i.e.*, derived from the local beachridges);
3. regional pollen; and
4. uncategorised pollen.

Wetland pollen included all species of wetland plants occurring either in the wetlands or along the margins of the wetlands of the Becher Suite (as described by C A Semeniuk *et al* 2006). Upland pollen included only the species of plants occurring on the beachridges of the Becher Cuspate Foreland which had been identified in surface pollen samples. Similarly, regional pollen included only species identified in the surface pollen. Species outside of these groups were assigned to uncategorised pollen.

Numbers of natural pollen counted within samples were transformed to pollen per 1 cm^3 by multiplying them by the ratio of the known amount of betulid pollen seeded in 1 cm^3 of sediment to the betulid pollen counted in any sample. A mathematical problem potentially occurs for natural pollen taxa with zero frequency in the volume of sample prepared. In multiplying the actual numbers of natural pollen recorded by the ratio derived from the seeded betulid pollen, zero still remains zero in contrast to all other taxa which increase proportionately. Natural pollen recorded as zero in a low volume of sediment potentially may have been detected in low numbers if larger samples of sediment had been used, or truly may be absent even in larger sediment volumes. Although we recognise this problem, we consider that if natural pollen was recorded as zero in the pollen counts then that species was probably low in abundance (or absent) anyway.

Given the large range in numbers of grains of the pollen taxa in a cubic centimetre of sediment, two diagram formats have been used to illustrate their numbers and composition down profile and between sites. In the first instance, all numbers of pollen were transformed using betulid pollen as an internal standard to generate numbers of pollen grains in a cubic centimetre of sediment and plotted using a logarithmic scale. Marked variations in pollen numbers down-profile are smoothed out, so that this method of presentation essentially shows absence/presence of all pollen down the profile and some broad measure of relative and comparative abundance for all species. In this context, small scale fluctuations in the graph represent abundance changes by factors, or by an order(s) of magnitude.

To highlight significantly abundant pollen numbers and to assist in the interpretation of the pollen record, a second method of presentation was used: only species with relatively higher frequencies of pollen per unit volume (*i.e.*, > 10^3 pollen grains per 1 cm^3, or > 3 on the logarithmic scale) were isolated and their abundance plotted arithmetically. In addition, so that pollen abundances could be readily compared at chronologically similar intervals, the stratigraphic columns were transformed so that they represent temporally evenly spaced sedimentary sections in 500-year increments.

A large number of radiometric dates in the Holocene wetland sedimentary sequences was available for this region (C A Semeniuk 2006), and so it was possible to determine mean rates of sediment accretion and assess/interpret the approximate location of the 500-year isochrons down the core profiles. Peaks in pollen numbers for the various species were correlated with radiocarbon dates of the sediments to facilitate inter-wetland comparisons. Where actual dates were not available, as described above, interpolated dates based on arithmetic proportioning of the sediment interval between two known dates were used. The stratigraphic columns in Figures 3, 4, 6, 7 & 8 thus illustrate the chronometrically partitioned sequences, the location of the pollen sampling sites against this chronometric adjusted framework, the location of the samples obtained for radiometric dating, and the abundance of the key species of pollen.

Background to the present palynological study, and stratigraphy of the wetland sites

Approximately 200 wetlands occur as basins in the inter-dune depressions of the Holocene beachridge plain in the Rockingham area (V & C Semeniuk Research Group 1991). Eighteen of these were studied in detail in terms of their landscape setting, stratigraphy, hydrology, hydrochemistry, and vegetation, (C A Semeniuk 2006) and 16 of this group were studied further by Semeniuk *et al* (2006) in terms of their pollen record in the surface sediment (as summarised below).

To provide a baseline for Holocene palynological studies for the Becher suite of wetlands from modern environments, *i.e.*, the pollen sources, the dispersion processes, pollen preservation, and palynological assemblages present in the surface sediments, the pollen assemblages in the surface sediments in the centre of 16 wetland basins in the Point Becher area were investigated by C A Semeniuk *et al* (2006). These authors (*op. cit.*) determined the ratio of wetland/upland species contributing to the surface pollen in each wetland, determined the contributions of local and regional pollen to the record, and identified indicator pollen assemblages to interpret fossil Holocene sequences. In the modern environment, the main wetland plant assemblages contributing to the pollen record included: 1. herblands of *Centella asiatica* (L.) Urb. in sumpland basin centres; 2. sedgelands of *Baumea articulata* (R. Br.) S. T. Blake in sumpland basin centres; 3. sedgelands of *Typha* (L.) spp.

in sumpland basin centres; 4. sedgelands of mixed *Baumea articulata* and *Typha* sp. in sumpland basin centres; 5. scrub of *Melaleuca teretifolia* Endl. in sumpland basin centres; 6. forest/shrubland of *Melaleuca rhaphiophylla* Schauer with understorey of *Centella asiatica* in centres or along margins of sumpland basins; 7. heath of *Melaleuca viminea* Lindley along sumpland basin margins; 8. stands of *Melaleuca cuticularis* Labill. in centres or along margins of sumpland basins; 9. fringing formations of *Xanthorrhoea preissii* Endl., with understorey of *Isolepis nodosa* (Rottb.) R. Br. and *Sporobolus virginicus* (L.) Kunth along sumpland and dampland basin margins; 10. sedgelands of *I. nodosa* along sumpland and dampland basin margins or in dampland basin centres; 11. grasslands of *Sporobolus virginicus* along sumpland and dampland basin margins; 12. mixed *I. nodosa* and *S. virginicus* along sumpland and dampland basin margins; 13. sedgelands of *Baumea juncea* (R. Br.) Palla along sumpland and dampland basin margins or in dampland basin centres; and 14. sedgelands of *Lepidosperma gladiatum* Labill. along sumpland and dampland basin margins.

The following key wetland plant species were commonly detected as pollen grains in the surface sediment in the 16 wetlands: *Baumea articulata, B. juncea, Centella asiatica, Isolepis nodosa, Lepidosperma gladiatum, Melaleuca cuticularis, M. viminea, M. rhaphiophylla, M. teretifolia, Sporobolus virginicus, Typha* spp. (as *T. domingensis* Pers. or *T. orientalis* C. Presl), and *Xanthorrhoea preissii*. C A Semeniuk *et al* (2006) separated the pollen assemblages recovered from the surface sediments into six categories as related to extant vegetation: 1. that generated *in situ* from wetland basin vegetation; 2. that derived from *in situ* wetland margin vegetation; 3. that derived allochthonously from wetland vegetation; 4. that from ridge vegetation and transported to the wetland basin; 5. that from vegetation outside the region; and 6. unidentified pollen. Most of the surface pollen in the wetlands was derived locally from the local wetland and upland vegetation of the cuspate foreland. Generally, *in situ* wetland pollen constituted a reasonable proportion of the total pollen. Wetland margin pollen was abundant in only half the wetlands. Pollen from local beachridges was sub-dominant to pollen from wetland species in about half the wetlands, and dominant in the remainder. The contribution of regional pollen varied from low in most wetlands to relatively high numbers locally.

The modern potential dispersal mechanisms for pollen in this area are easterly and westerly winds, rain, insects, and avifauna, and local processes of *in situ* generation, sheet wash, and water transport. The differential effect of wind in transporting pollen was explored by C A Semeniuk *et al.* (2006) using local wetland species of *Melaleuca* as a signature, and the occurrence of upland species and regional, such as Casuarinaceae spp., *Olearia axillaris* (DC.) F. Muell. ex Benth., and *Eucalyptus marginata* Donn ex Smith pollen. The patterns show that delivery of pollen to the modern surface sediments of the wetland basins is heterogeneous.

Table 1

Description of wetlands in this study in terms of location relative to age structure, local geomorphic setting, wetland type, sedimentary fill, and vegetation

Wetland	Age Setting	Local geomorphic setting	Wetland type	Sediment fill	Extant vegetation (structurally, and numerically dominant species)
161	oldest, eastern part of suite; age of base of sedimentary fill is mid Holocene, *circa* 4300 ^{14}C years	relatively high beachridges border east and west margins	sumpland	incipient peat at surface and underlain by calcilutite, and basal calcilutaceous muddy sand	*Baumea articulata*
162	oldest eastern part of suite; age of base of sedimentary fill is mid Holocene, *circa* 4100 ^{14}C years	relatively high beachridges border east and west margins	sumpland	calcilutite, and basal calcilutaceous muddy sand	*Melaleuca teretifolia*
163	younger wetland in eastern part of suite; age of base of sedimentary fill is mid-late Holocene, *circa* 2900 ^{14}C years	relatively high beachridges border east and west margins	sumpland	calcilutite, and basal calcilutaceous muddy sand	*Juncus kraussii*
135	middle part of suite; age of base of sedimentary fill is mid-late Holocene, *circa* 2600 ^{14}C years	relatively high beachridge borders east margin; low beachridge on west margin	sumpland	calcilutite, and basal calcilutaceous muddy sand	*Melaleuca rhaphiophylla, Centella asiatica*
9–14	western part of suite; age of base of sedimentary fill is mid-late Holocene, *circa* 2400 ^{14}C years	low beachridges border east and west margins	sumpland	calcilutite, and basal calcilutaceous muddy sand	*Juncus kraussii*

The stratigraphy of the 5 wetlands selected for palynological study and location of samples for radiometric dating in the cores are shown in Figure 2. The setting of these wetlands is described in Table 1. Sediment terms are after Semeniuk & Semeniuk (2004)

The use of surface and near surface pollen assemblages as a baseline for interpreting fossil wetland pollen sequences

Description and interpretation of the pollen records for the near surface sediments in relation to extant vegetation in wetlands 161, 162, 163, 135 and 9–14 are provided in Tables 2 to 6. Given that there is vertical mixing, the pollen record in the surface and near-surface sediment (*i.e.*, the immediate surface sediment < 1 cm depth, 3–5 cm depth, and 10 cm depth) was noted against the extant wetland vegetation for a given wetland basin to be able to discriminate between the combined effects of *in situ* pollen production, import from other areas by wind, and contribution by vertical mixing (bioturbation). If a species was represented in the surface and near surface pollen but not present in the extant wetland vegetation for a given basin, note was then made of the likely source of pollen from other proximal and distal wetlands. The occurrence of particular pollen species in surface and near surface sediment when that plant species is absent in the wetland may be explained by 1) transportation into the basin by wind, 2) a sub-recent occurrence in the basin, or 3) bioturbation into the surface layers from depths > 10 cm.

The pollen data have been reduced so that only the most abundant species for any sample are presented, and the species at any sampling interval are ordered in terms of their abundance. The analyses of relative pollen abundance in the Tables 2–6 are presented in terms of the relative stratigraphic sequence of surface (0–2 cm), near surface (3–5 cm), and at 10 cm depth, without any connotation as to absolute ages.

From the analyses in Tables 2–6, it is concluded that the following vegetation assemblages and their marginal components will be reflected in the pollen record, and can be used to interpret past vegetation patterns:

1. *C. asiatica* herb assemblage
2. *B. articulata* sedge assemblage
3. *Typha* sp. sedge assemblage
4. mixed *B. articulata* and *Typha* sp. sedge assemblage
5. *M. teretifolia* scrub assemblage
6. *M. rhaphiophylla* forest/shrub assemblage, with understorey of *C. asiatica*
7. *M. viminea* heath assemblage
8. *M. cuticularis* assemblage
9. wetland margin of *X. preissii*, *I. nodosa* and *S. virginicus* assemblages.

Descriptions of patterns down profile for total wetland pollen and upland pollen

The description of the pollen down the stratigraphic profile is provided below as total pollen down the profile, and as the composition of this pollen in terms of wetland, upland, regional, and uncategorised, and specific patterns for a given species. When viewing the total numbers of pollen down the profile (Fig. 3), it is also important to note the relative proportion of wetland, upland, and regional pollen contributing to this record (Fig. 4).

In wetland 161, excluding the surface pollen, numbers

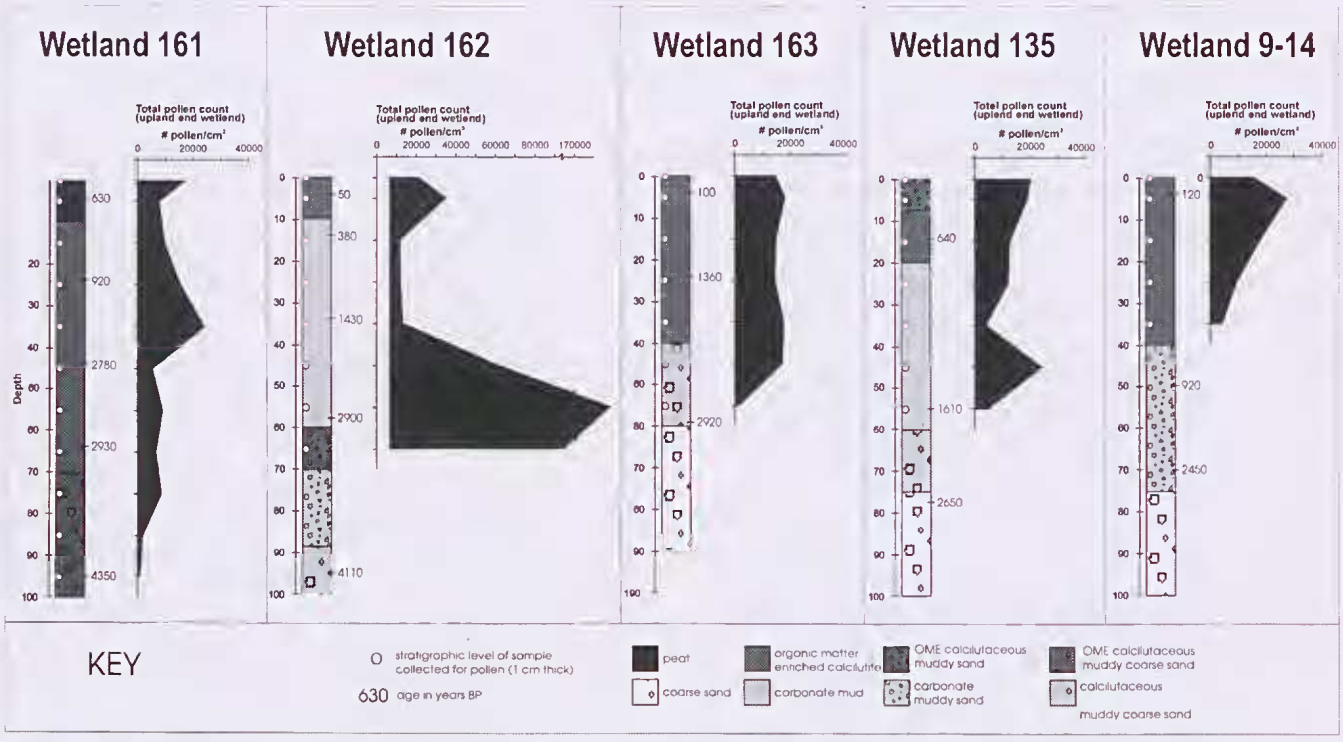


Figure 3. Total pollen down the stratigraphic profile for the five wetlands studied. The scale for pollen numbers is arithmetic.

Table 2

Wetland 161 – description and interpretation of the pollen record of surface and near-surface sediment in relation to intra-basinal extant vegetation, other proximal and distal wetland basins, and other physical processes

Wetland 161
Extant vegetation (most abundant species): *B. articulata*
Extant vegetation (less abundant, or on margins): *X. preissii, B. juncea, T. domingensis, T. orientalis, C. asiatica, S. virginicus*

Species occurrence (most abundant species):	Correlation of extant and fossil pollen	Extant plant taxa missing from record	Extra-basinal or sub-recent contribution	Comments
Pollen in surface sediment: *B. articulata, X. preissii, C. asiatica, Typha* sp.	contemporary record reflects dominant extant species, and *X. preissii* on margins	*B. juncea* (the species is too sparse in the modern vegetation); *S. virginicus*	*M. rhaphiophylla*	contemporary record suggests pollen reflects vegetation history; *M. rhaphiophylla* is a sub-recent component, or wind-derived; the nearest basins with this species are 135 and 136, from which pollen could be delivered via seabreezes
Pollen at 3–5 cm: *B. articulata, C. asiatica, Typha* sp., *X. preissii, S. virginicus*	pollen record reflects extant species, with more prominent contribution from margins	*B. juncea*	none	Fossil pollen suggests similar vegetation to present
Pollen at 10 cm: *B. articulata, C. asiatica, Typha* sp., *X. preissii, Triglochin* sp.	record reflects all extant species, with *Triglochin* mixed in from depth	*B. juncea*	none	Fossil pollen suggests similar vegetation to present

Table 3

Wetland 162 – description and interpretation of the pollen record of surface and near-surface sediment in relation to intra-basinal extant vegetation, other proximal and distal wetland basins, and other physical processes

Wetland 162
Extant vegetation (most abundant species): *M. teretifolia, C. asiatica, B. juncea*
Extant vegetation (less abundant, or on margins): *X. preissii, S. virginicus, I. nodosa*

Species occurrence (most abundant species):	Correlation of extant and fossil pollen	Extant plant taxa missing from record	Extra-basinal or sub- recent contribution	Comments
Pollen in surface sediment: *M. teretifolia, C. asiatica, X. preissii, B. juncea, M. rhaphiophylla, M. viminea, I. nodosa*	contemporary record reflects dominant extant species, and *X. preissii* on margins	*S. virginicus, I. nodosa*	*M. rhaphiophylla* and *M. viminea*	contemporary record suggests pollen reflects vegetation history; *M. rhaphiophylla* and *M. viminea* probably are sub-recent components, or wind derived; the nearest basins with these species are 135 and 136, from which pollen could be delivered via seabreezes
Pollen at 3–5 cm: *I. nodosa, X. preissii, C. asiatica, M. rhaphiophylla, B. juncea*	pollen record partly reflects extant species, with more prominent contribution from margins	*M. teretifolia*, indicating its absence from fossil vegetation assemblages at 5 cm depth	*M. rhaphiophylla*	fossil pollen suggests *M. rhaphiophylla* with broadly similar understorey to the present assemblage; the lack of *M. teretifolia* suggests that surface pollen has not been mixed down to 5 cm
Pollen at 10 cm: *B. juncea, M. rhaphiophylla, I. nodosa*	record reflects some extant species	*M. teretifolia, C. asiatica*	none	fossil pollen suggests *M. rhaphiophylla* with broadly similar understorey to the present assemblage; lack of *M. teretifolia* suggests no mixing of surface pollen to 10 cm

Table 4

Wetland 163 – description and interpretation of the pollen record of surface and near-surface sediment in relation to intra-basinal extant vegetation, other proximal and distal wetland basins, and other physical processes

Wetland 162
Extant vegetation (most abundant species): *J. kraussii, C. asiatica, B. juncea*
Extant vegetation (less abundant, or on margins): *X. preissii, S. virginicus, I. nodosa, M. teretifolia*

Species occurrence (most abundant species):	Correlation of extant and fossil pollen	Extant plant taxa missing from record	Extra-basinal or sub- recent contribution	Comments
Pollen in surface sediment: *I. nodosa, C. asiatica, S. virginicus, B. juncea, X. preissii, M. rhaphiophylla*	contemporary record reflects minor components of extant species and extant assemblages, and dominantly from the margins	*J. kraussii* (because of its poor preservation)	*M. rhaphiophylla M. teretifolia* (the latter is too sparse in the modern vegetation)	leaving aside *J. kraussii*, the contemporary record suggests pollen reflects vegetation history, with *M. rhaphiophylla* and *M. teretifolia* as a sub-recent component
Pollen at 3–5 cm: *C. asiatica, I. nodosa, S. virginicus, B. articulata, X. preissii*	pollen record largely reflects extant species, with more prominent contribution from margins	*J. kraussii* (because of its poor preservation)	*B. articulata*	fossil pollen suggests vegetation was *C. asiatica – B. articulata* dominated; the possibility that *B. articulata* is exogenic is rejected because the nearest basin (161) with this species is in the wrong direction for wind delivery, and the intervening basin (162) is devoid of its pollen
Pollen at 10 cm: *C. asiatica, S. virginicus, M. viminea*	record reflects some extant species	*J. kraussii* (because of its poor preservation), *B. juncea, X. preissii, S. virginicus, I. nodosa, M. teretifolia*	*M. viminea*	fossil pollen suggests vegetation was *C. asiatica – M. viminea* dominated with contributions from the margin by *I. nodosa* and *S. virginicus*

Table 5

Wetland 135 – description and interpretation of the pollen record of surface and near-surface sediment in relation to intra-basinal extant vegetation, other proximal and distal wetland basins, and other physical processes

Wetland 135
Extant vegetation (most abundant species): *M. rhaphiophylla, C. asiatica, J. kraussii, B juncea*
Extant vegetation (less abundant, or on margins): *X. preissii, S. virginicus, I. nodosa*

Species occurrence (most abundant species):	Correlation of extant and fossil pollen	Extant plant taxa missing from record	Extra-basinal or sub-recent contribution	Comments
Pollen in surface sediment: *S. virginicus, M. rhaphiophylla, I. nodosa, M. viminea, B. juncea*	contemporary record reflects extant species	*J. kraussii, C. asiatica* and *X. preissii*	*M. viminea*	leaving aside *J. kraussii*, contemporary record suggests pollen partly reflects vegetation history; *C. asiatica* has recently returned to this wetland; *M. viminea* is a sub-recent component, or wind derived, with the source as wetland 9–11
Pollen at 3–5 cm: *I. nodosa, M. cuticularis, M. rhaphiophylla, S. virginicus, X. preissii*	pollen record only partly reflects extant species	*J. kraussii, C. asiatica*	*M. cuticularis*	pollen suggests vegetation was *M. rhaphiophylla* dominated; *M. cuticularis* may be exogenic, but being in only a specific horizon suggests *in situ* accumulation
Pollen at 10 cm: *C. asiatica, X. preissii, M. viminea, S. virginicus*	record reflects extant species	*J. kraussii*	none	fossil pollen suggests vegetation was *C. asiatica – M. viminea* dominated, with contributions from margins by *X. preissii* and *S. virginicus*

Table 6

Wetland 9–14 – description and interpretation of the pollen record of surface and near-surface sediment in relation to intra-basinal extant vegetation, other proximal and distal wetland basins, and other physical processes

Wetland 9–14
Extant vegetation (most abundant species): *J. kraussii*
Extant vegetation (less abundant, or on margins): *C. asiatica, X. preissii, S. virginicus, I. nodosa, M. viminea*

Species occurrence (most abundant species):	Correlation of extant and fossil pollen	Extant plant taxa missing from record	Extra-basinal or sub- recent contribution	Comments
Pollen in surface sediment: *M. viminea, S. virginicus, I. nodosa, C. asiatica, X. preissii*	contemporary record does not reflect extant species	*J. kraussii*	*M. viminea, X. preissii*	leaving aside *J. kraussii*, contemporary record suggests pollen will reflect vegetation history
Pollen at 3–5 cm: *I. nodosa, Typha* sp.	pollen record does not reflects central basin extant species, but only margin species	*J. kraussii, C. asiatica*	*Typha* sp.	fossil pollen suggests vegetation was *Typha* sp.
Pollen at 10 cm: *I. nodosa, C. cuticularis*	record reflects only one extant species of the margins	*J. kraussii*	*M. cuticularis*	fossil pollen gives no clear indication of vegetation composition; *M. cuticularis* may be *in situ*, or wind transported, and it is difficult to separate the two

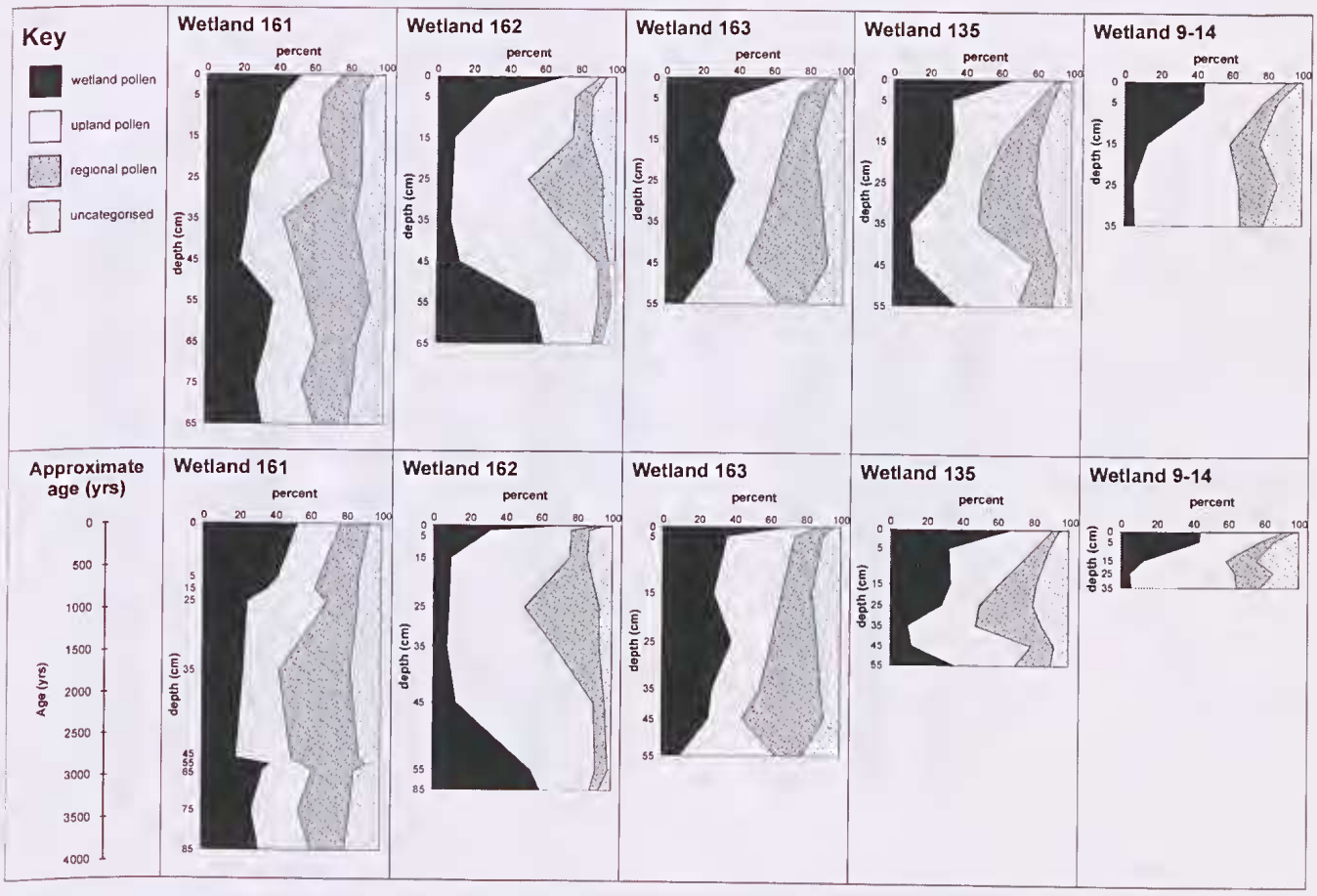


Figure 4. Graphs showing the composition of the pollen down the stratigraphic profile in terms of wetland pollen, (local) upland pollen, regional pollen and uncategorised pollen. The upper part of the diagram presents the data at true depth from the surface; the lower part represents the data on a chronometrically adjusted scale.

of pollen down profile increased to 35 cm then decreased at 45 cm and decreased again at 85 cm (Fig. 3). The highest values at 35 cm occurred as a result of general increases in subequal amounts in pollen from all categories, and particularly from regional pollen. In wetland 162, excluding the surface pollen, numbers of pollen down profile exhibited two peaks, a moderate one at 5 cm dominated by pollen from wetland and upland (ridge) species, and a large one at 55 cm, dominated by wetland species. In wetland 163, numbers of pollen down profile were fairly consistent to 45 cm, before falling sharply at 55 cm. In wetland 135, numbers of pollen down profile decreased from the surface to 35 cm, peaked at 45 cm, and decreased again at 55 cm. The higher numbers at 45 cm were due to upland pollen. The pollen numbers from wetland species down profile were low. In wetland 9–14, numbers of pollen down profile increased at 5 cm as a result of higher numbers of pollen from wetland and ridge species, then decreased.

Table 7

Total pollen numbers in each sediment type at different sites

Site and depth (cm)	Numbers of pollen/cm^3	Sediment type, or soil
162–45	54,000	buried soil
162–55	181,000	buried soil
162–65	88,000	buried soil
162–5	28,000	organic matter enriched calcilutite (organic matter dominated, *i.e.*, incipient peat)
161–5	7,500	organic matter enriched calcilutite
161–15	10,000	organic matter enriched calcilutite
161–25	15,000	organic matter enriched calcilutite
161–35	24,000	organic matter enriched calcilutite
163–5	18,000	organic matter enriched calcilutite
163–15	15,000	organic matter enriched calcilutite
163–25	14,000	organic matter enriched calcilutite
163–35	18,000	organic matter enriched calcilutite
163–45	17,000	organic matter enriched calcilutite
135–5	19,000	organic matter enriched calcilutite
9–14–5	27,000	organic matter enriched calcilutite
9–14–15	18,000	organic matter enriched calcilutite
135–15	12,000	organic matter enriched calcilutite and calcilutite
162–15	5,000	organic matter enriched calcilutite and calcilutite
161–45	5,000	calcilutite
161–55	9,000	calcilutite
161–65	6,500	calcilutite
161–75	8,500	calcilutite
161–85	2,000	calcilutite
162–25	5,000	calcilutite
162–35	6,000	calcilutite
135–25	12,000	calcilutite
135–35	4,000	calcilutite
135–45	28,000 (anomaly)	calcilutite
135–55	5,000	calcilutite
163–55	1,000	calcilutaceous muddy sand
161–95	1,000	calcilutaceous muddy sand
9–14–25	9,000	calcilutaceous muddy sand
9–14–35	4,000	calcilutaceous muddy sand

In absolute terms, the variation in pollen numbers with respect to sediment composition showed an interesting relationship. In Table 7, pollen numbers, ordered from highest to lowest, are shown to be related to groups of sediment types and buried soil. Pollen numbers in buried soils were highest, followed by incipient peat and organic matter enriched calcilutite (ranging from 10,000–24,000 pollen per cm^3) which were also relatively consistent from site to site, both essentially reflecting high pollen production rates in wetlands with high plant production rates (culminating in the formation of peat and organic matter enriched calcilutite). Pollen numbers decreased in calcilutite (5,000–12,000 pollen per cm^3) and in calcilutaceous muddy sand (1,000–9,000 pollen per cm^3). The pollen numbers for sample 135–45 (calcilutite) were abnormally high, and are more characteristic of buried soils. At this site, high numbers of pollen from upland vegetation caused the marked increase in pollen abundance.

However, there were instances where the abundances of total pollen down profile also fluctuated within lithology, or did not markedly vary across some lithologic contacts (Fig. 3). The main peak in pollen abundance (24,000 pollen grains/cm^3) down profile in wetland 161, for example, occurs within a lithologically homogeneous sequence of organic matter enriched calcilutite. The largest peak in pollen abundance (181,000 pollen grains/cm^3) in wetland 162 occurs across a lithological boundary, being partly in organic matter enriched calcilutaceous muddy sand and partly in calcilutite. Generally in organic matter enriched calcilutite, pollen abundance is more or less uniform (± 15,000–20,000 pollen grains/cm^3). The high peak in abundance (28,000 pollen grains/cm^3) down profile in wetland 135 occurs in a distinct band within a lithologically homogenous sequence of calcilutite. The abundance of pollen grains in wetlands 9–14 decreases down the stratigraphic profile within a lithologically homogenous sequence of organic matter enriched calcilutite. In more detail, Figure 3 shows peaks in pollen abundance in wetland 161 occurring in calcilutite and organic matter enriched calcilutaceous muddy sand. In wetland 162 peaks occur in organic matter enriched calcilutite, calcilutite and a buried soil, in wetland 163 peaks occur in organic matter enriched calcilutite and calcilutaceous muddy sand, in wetland 135 peaks occur in calcilutite, and in wetland 9–14 peaks occur in organic matter enriched calcilutite.

The following wetland species, occurring in the central wetland habitats or wetland margin habitats, were sufficiently common and present in the samples for use in analyses in Figures 5–7: *B. articulata*, *B. juncea*, *C. asiatica*, *I. nodosa*, *L. gladiatum*, *M. cuticularis*, *M. rhaphiophylla*, *M. teretifolia*, *M. viminea*, *S. virginicus*, *Triglochin* sp, *Typha* spp (as *T. domingensis* or *T. orientalis*), *Xanthorrhoea preissii*, Cyperaceae spp. The following upland species, derived from local beachridges, or distally in the region, were sufficiently common and present in the samples for use in analyses in Figures 5–8: *Acacia cyclops* Cunn. ex Don, *Adriana quadripartita* (Labill.) Gaudich., Casuarinaceae sp., Chenopodiaceae sp 1, Chenopodiaceae sp 2, *Eucalyptus marginata*, Myrtaceae sp 1, *Olearis axillaris*, and *Stipa flavescens* Labill.

Figure 5. Graphs showing the composition of the various species of wetland pollen, upland pollen and regional pollen down the stratigraphic profile for each of the wetlands 161, 162, 163, 135, and 9–14. The upper part of each diagram (A) is of wetland pollen, the lower part (B) is of upland pollen and regional pollen. The scale for pollen numbers is logarithmic.

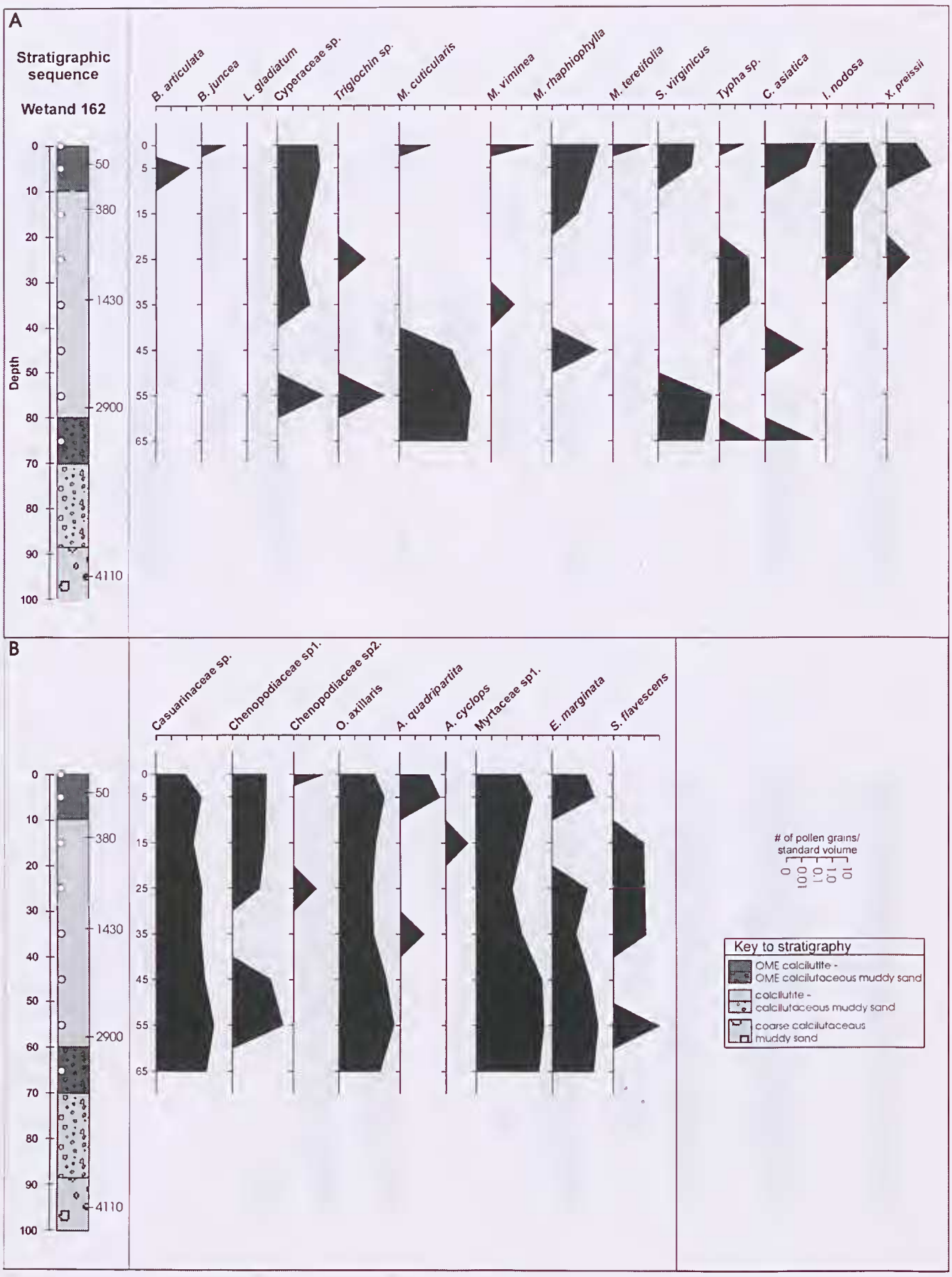


Figure 5 (cont.)

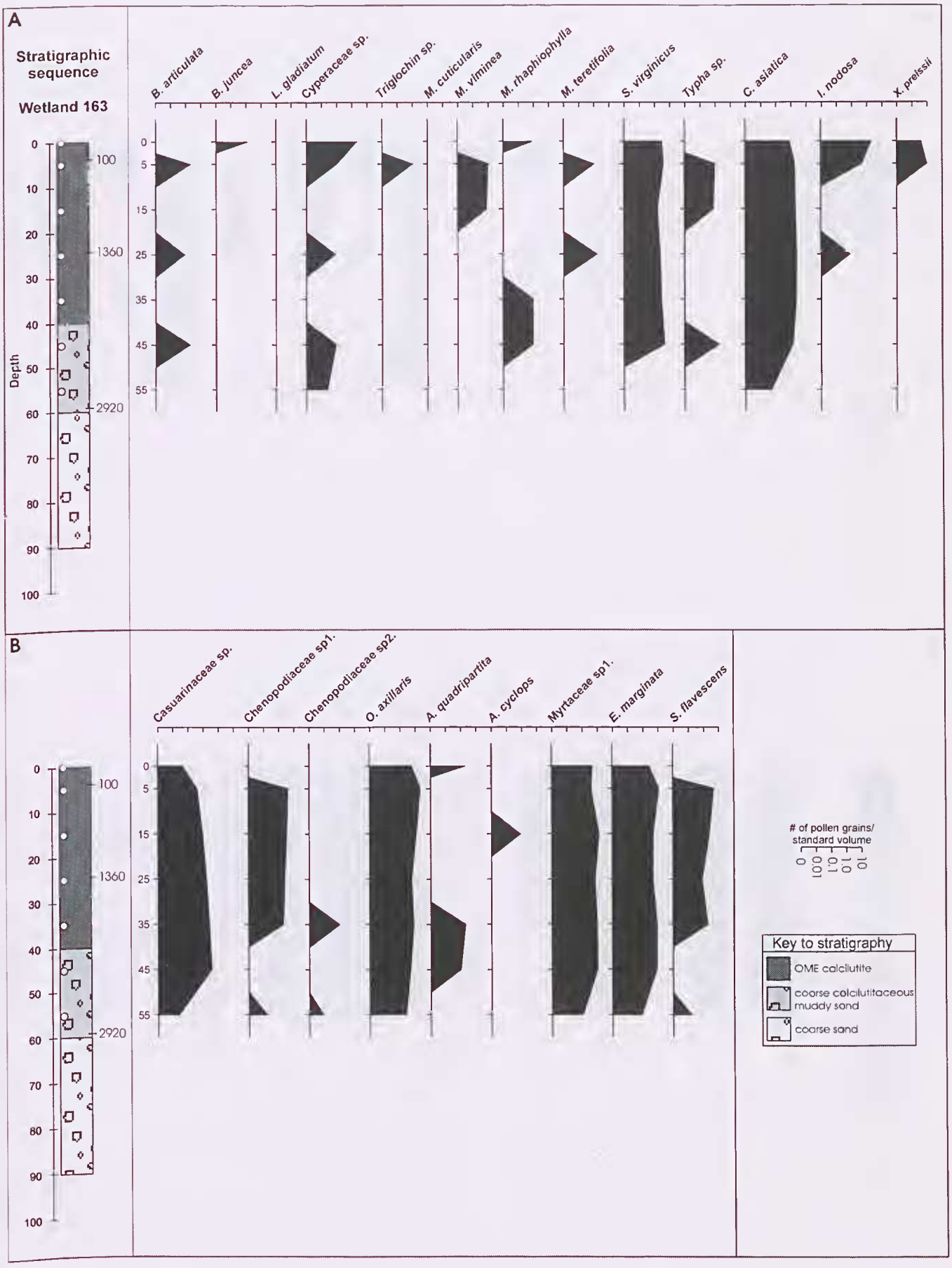


Figure 5 (cont.)

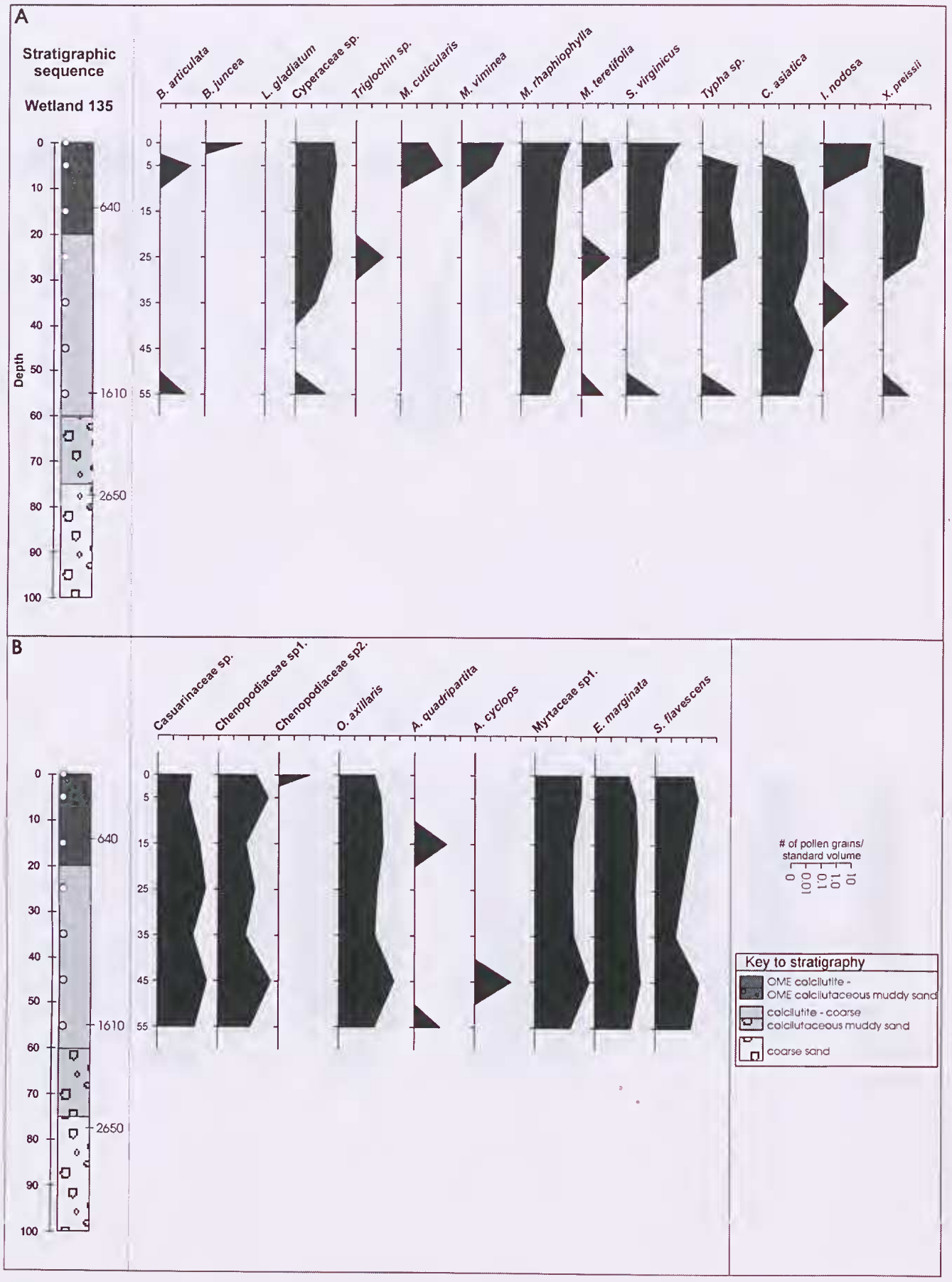


Figure 5 (cont.)

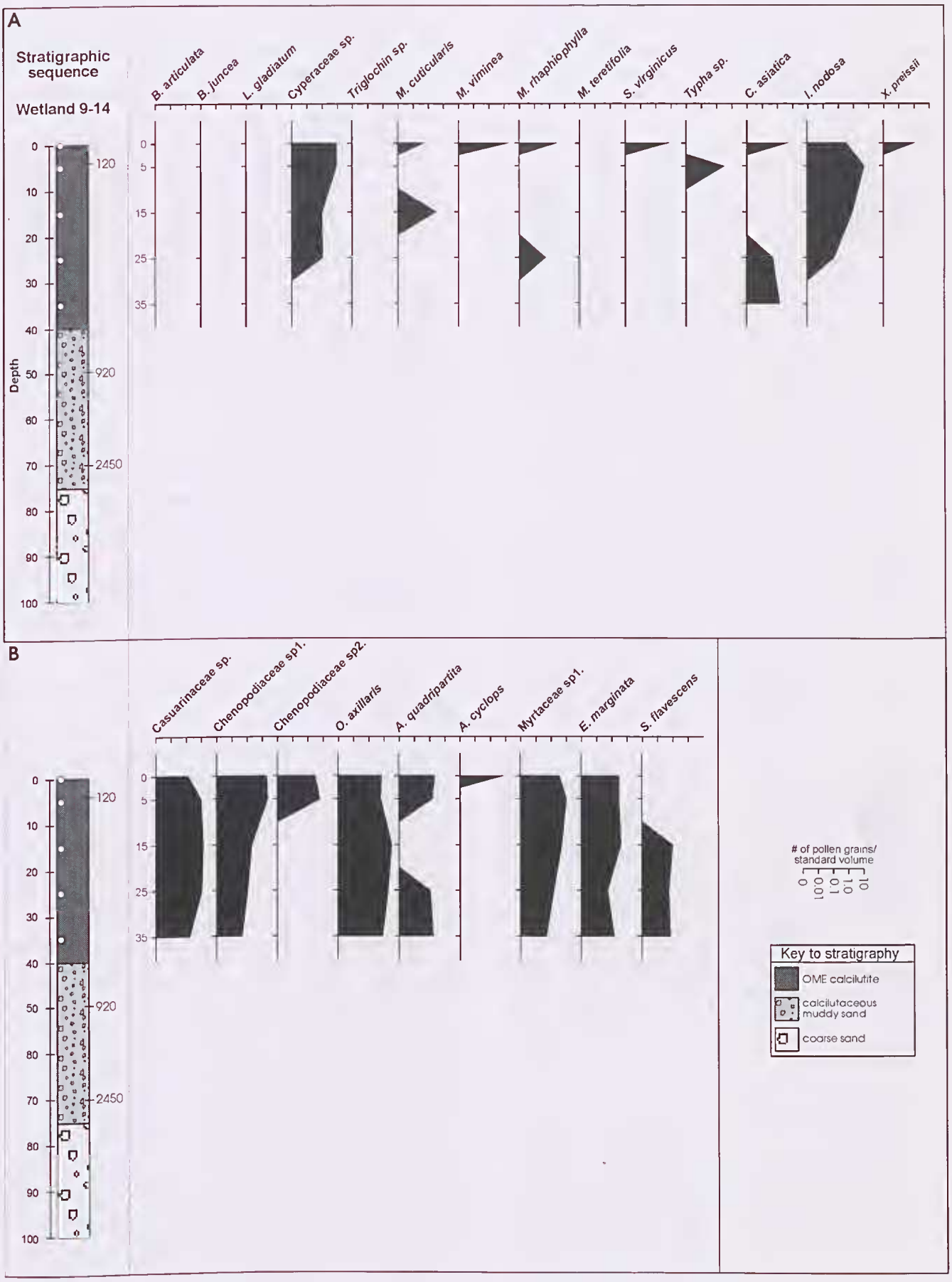


Figure 5 (cont.)

In wetland 161, the wetland pollen numbers for individual species down profile were low. Two of the taxa were consistently present, *C. asiatica* and *S. virginicus*, the former whose numbers were in greater abundance, albeit fluctuating, and the latter, whose numbers were low and consistent. Of the other species which presently colonise the wetland, *B. articulata* was present in the surface layers and in minor amounts in the lower part of the profile, *L. gladiatum* was present to 35 cm, *X. preissii* to 15 cm, and *Typha* sp. to 65 cm (Fig. 5). The interval 35–65 cm was characterised by wetland species which are not extant in wetland 161, *i.e.*, *Melaleuca* spp. and *Triglochin* sp. From 0–15 cm and 55–85 cm, pollen derived from wetland species exceeded pollen derived from ridge species, the major families being Cyperaceae, Umbelliferae and Poaceae. Pollen derived predominantly from ridge species was relatively consistent down profile, with slight increases at 15, 25, and 35 cm, and a decrease at 95 cm. Pollen derived from regional vegetation increased at 25 and 35 cm.

In wetland 162, the wetland pollen numbers down profile ranged from high to low. None of the pollen taxa was continuously present. Of the species which presently colonise the wetland, *M. teretifolia* was present only in the surface layer, *C. asiatica* was present in the surface layer and exhibited a peak at 65 cm, and *X. preissii* did not occur below 25 cm (Fig. 5). The interval 15–45 cm was characterised by low numbers of wetland pollen, while the interval 45–65 cm, which exhibited the major peak, was characterised by species which do not currently occur in wetland 162, *i.e.*, species of *Melaleuca* other than *M. teretifolia*, and *Triglochin* sp. Pollen from ridge species and pollen derived from regional vegetation increased at 45 and 55 cm, paralleling the increase in total pollen numbers.

For individual species, in wetland 163, the wetland pollen numbers down profile were low and dominated by pollen from *C. asiatica*, *S. virginicus* and *C. asiatica*, which presently colonise the wetland, were consistently present throughout the profile and showed only minor fluctuation. Of the other species which presently colonise the wetland, no pollen of *J. kraussii* was found, Cyperaceae spp. (which potentially includes *B. juncea*) was present in the surface layers and in minor amounts in the lower part of the profile, and *X. preissii* did not occur below 5 cm (Fig. 5). Pollen from various ridge species did not show any consistent pattern down profile. Compositae displayed alternate increases and decreases down profile, while few pollen from Chenopodiaceae and Poaceae occurred below 35 cm. A slight increase in overall numbers of pollen from the ridges occurred at 35 cm. Pollen derived from regional vegetation increased at 45 cm.

In wetland 135, *M. rhaphiophylla* and *C. asiatica*, which colonise the wetland, were the only species consistently present throughout the sediment profile and both showed fluctuations. Of the other species which presently colonise the wetland, those of Cyperaceae were present in most layers, in minor amounts, *S. virginicus* was highest in the surface layer and decreased down profile, and *X. preissii* occurred between 5 and 25 cm and again at 55 cm (Fig. 5). The composition of the wetland pollen varied down the profile, with dominance by all four species of *Melaleuca* at the surface changing to dominance by *C. asiatica* and *M. rhaphiophylla* at 45 cm. Except at the surface, pollen derived from species on the ridges exceeded wetland pollen, with a minor peak at 5 cm and a second higher peak at 45 cm comprising Chenopodiaceae, Compositae, and Poaceae. Pollen derived from regional vegetation increased at 45 cm.

For individual species, in wetland 9–14, the numbers of wetland pollen down profile were low. Pollen from Cyperaceae and *I. nodosa*, which currently colonise the wetland, were consistently present to 25 cm (Fig. 5). The patterns in these two taxa mirrored the overall population pattern. No pollen of *J. kraussii*, the species that currently dominates the wetlands, was found. Pollen from ridge species showed dissimilar frequency patterns down profile, Compositae pollen increased to 15 cm then decreased, while Chenopodiaceae pollen increased at 5 cm then remained consistent. A slight increase in pollen from the ridges occurred at 5 cm. Pollen derived from regional vegetation was relatively consistent down profile with a slight increase at 15 cm.

Patterns of species abundance down profile in relation to age structure

Pollen abundances down profile were graphed in relation to the ages determined for each core to construct the palynological history in individual wetlands, and in order to compare patterns in a single species across wetlands, in pollen categories, and in species associations within a framework of (reconstructed) temporally equivalent isochrons (Figs 6–8).

Palynology of individual wetlands with respect to selected species

Pollen abundance against age structure in wetland 161 (Figs 6A & 7A) indicates that the extant species, *i.e.*, *B. articulata* and *C. asiatica*, were present in the early stage of wetland development (4350 ^{14}C yrs BP), but that *X. preissii* is a relatively recent arrival (920 ^{14}C yrs BP to the present). The extant assemblages appear to have replaced sub-recent assemblages of *Melaleuca* species. The surface sediments (0-5 cm) in wetland 161 span over 600 years in contrast to the other wetlands in which the equivalent interval spans 100–200 years. This suggests that pollen species recorded in the surface layer of 161 are likely to be from a sequential series of plant assemblages, whereas in other wetlands the potential mixture of recent and sub-recent plant assemblages will be less. In wetland 162, the pollen record indicates that the extant species, *i.e.*, *M. teretifolia* and *X. preissii* are also relatively recent (< 1000 years), again having replaced other *Melaleuca* species (Figs 6B & 7B). The early plant assemblages contained *C. asiatica*, *Typha sp.*, *M. cuticularis*, and *S. virginicus*. The first two species are likely to be related to the buried soil horizon and the latter two species to the commencement of carbonate mud deposition. In wetland 163, the pollen record indicates that some of the extant species, *C. asiatica* and *S. virginicus*, were present from the time of wetland initiation up to the present, and others are relatively recent arrivals, *X. preissii* (Figs 6C & 7C). *Melaleuca* pollen occurs in the sub-recent. In wetland 135, the pollen record indicates that the extant species, *M. rhaphiophylla* and *C. asiatica*, were present near the beginning of

wetland development (Figs 6D & 7D), together with a number of other species. Pollen from several species of *Melaleuca* occurs in the sub-recent. For wetland 9–14, it is not possible to determine the colonisation period for *J. kraussii* (Figs 6E & 7E), but *C. asiatica* was again an early coloniser. Although the pollen from plants in the current wetland assemblages is present throughout the stratigraphic cores, the earliest record of the two marginal species, *I. nodosa* and *X. preissii*, in the Becher area is *circa* 1500 ^{14}C yrs BP.

Correlation between basins of patterns for selected pollen species in three pollen categories

The peaks in the down profile abundance of selected species drawn from three categories of pollen, *viz.*, wetland, ridge, and wetland margin, were examined. The two wetland pollen species which were most consistent throughout the wetland cores, *C. asiatica* and *S. virginicus*, together with *M. rhaphiophylla*, *M. viminea* and *Triglochin* sp., were selected, and patterns were compared within each wetland basin and between wetlands. Pollen of three species deriving from upland vegetation were selected: Casuarinaceae, which would indicate aeolian transport from the east; *O. axillaris* which would indicate aeolian transport from the west; and *Stipa flavescens* which indicates aeolian transport or sheet wash input from local ridges. The third group consisted of species of plants which currently colonise the wetland margins and/or invade the wetlands during periods of below average rainfall, *X. preissii* and *Adriana quadripartita* (Labill.) Gaudich.

The peaks in pollen abundance down profile for selected wetland species, as distinct from total pollen numbers, did not relate to sediment type. For example, Figure 7A shows the peaks in abundance in *C. asiatica* in wetland 161 occurring in calcilutaceous muddy sand and in organic matter enriched calcilutite, whereas Figure 7D shows the peaks in abundance of the same species in wetland 135 to occur in organic matter enriched calcilutite and in calcilutite. For *M. cuticularis*, the peak in abundance crosses two lithologic types (organic matter enriched calcilutaceous muddy sand, and calcilutite).

There appears to be some co-incidence in timing of increased abundance of several wetland species within a wetland basin, *e.g.*, in wetland 161 there were concurrent peaks in four of the five selected wetland species, *C. asiatica*, *S. virginicus*, *M. rhaphiophylla* and *M. viminea* *circa* 1800 ^{14}C yrs BP. However, there was less agreement between basins, *e.g.*, *C. asiatica* showed peaks in wetlands 161 and 163 around 1800 ^{14}C yrs BP, but not in wetlands 162 or 135. Similarly, there was a peak in *S. virginicus* pollen in wetland 163 *circa* 2160 ^{14}C yrs BP which was not evident in any of the other wetlands.

There also appears to be some co-incidence in timing for increased abundance in pollen of upland species within a single basin, *e.g.*, in wetlands 135 and 162 there were concurrent peaks in the three species *circa* 1370 and 2900 ^{14}C yrs BP, respectively. There was only intermittent co-incidence in timing for increased abundance in pollen between wetlands, *e.g.*, peaks occurring at *circa* 2900 ^{14}C yrs BP in wetlands 162 and 163. The dates for peaks in wetland 9–14 suggest that the frequency of peaks may be greater if sampling was undertaken at a narrower interval.

The peaks in abundance down profile for the marginal species such as *I. nodosa*, *S. virginicus*, and *M. viminea*, were more frequent than either of the other two categories. There was some agreement between the timing of peaks in that, for many, there was a corresponding occurrence in at least one other wetland basin.

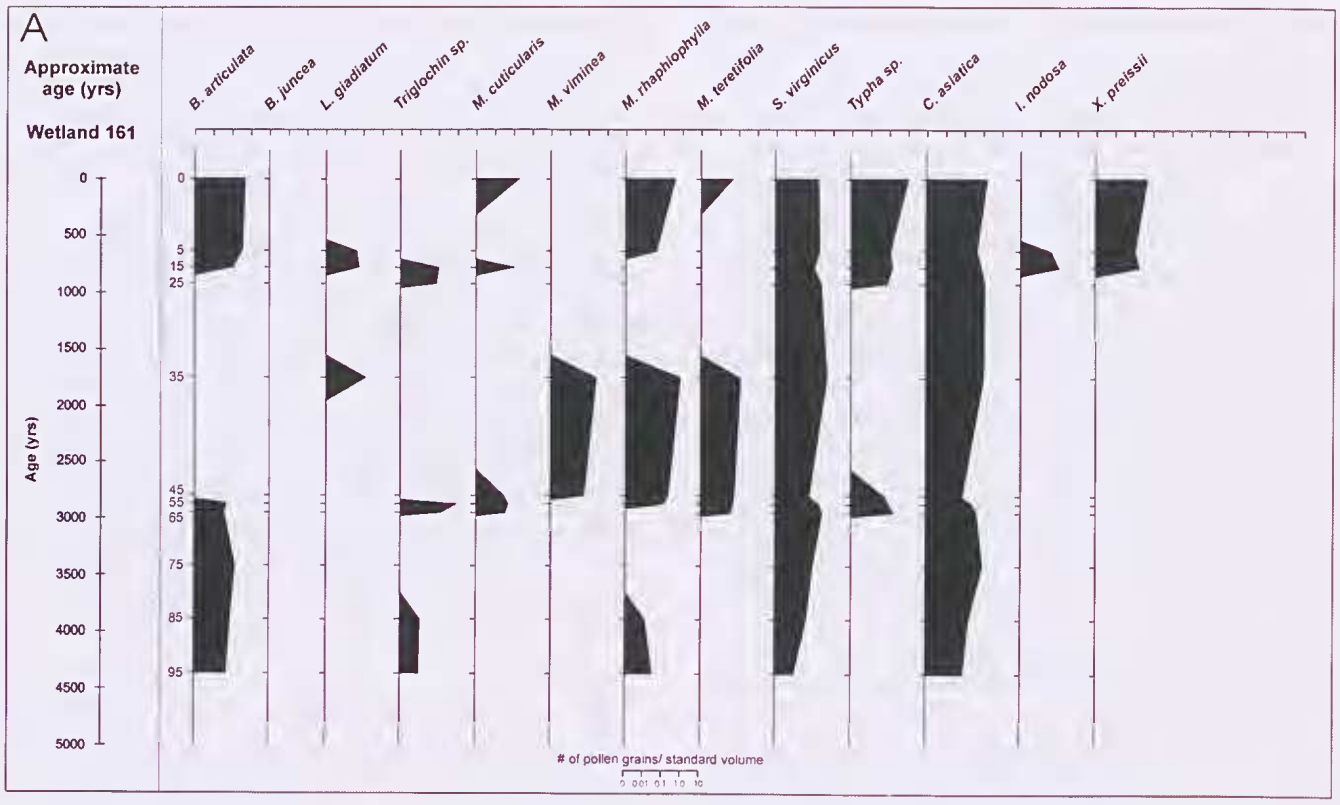
From the beginning of wetland development to the present, the species composition of both subregional (upland, beachridge) and regional pollen contribution is similar, but there have been changes in abundance. For example, in wetland 162, there was a 1000-year period in which Casuarinaceae pollen increased, reaching its maximum abundance *circa* 2900 ^{14}C yrs BP. This was briefly reflected in wetland 161, in which two additional increases in regional pollen occurred. In wetland 163, there was also a 1000 year period in which Casuarinaceae pollen increased, reaching its maximum abundance *circa* 2100 ^{14}C yrs BP. In wetland 135 peaks in numbers of Casuarinaceae pollen occurred *circa* 900 and 1400 ^{14}C yrs BP, and in wetland 9–14, a peak occurred recently.

Interpretation of results

As noted above, total pollen numbers varied with respect to sediment type and soils: pollen numbers were highest in buried soil horizons, followed by those in incipient peat and organic matter enriched calcilutite, which were also relatively consistent from site to site. Pollen numbers decreased in calcilutite and in calcilutaceous muddy sand. The abundance of wetland pollen in relation to sediment type and soils reflects the productivity of plant material (producing organic matter enriched substrates, incipient peats, and soils) which in turn results in increased production of *in situ* wetland pollen.

Down profile variation in abundance of wetland species pollen and inter-basin variation of these species at isochronous levels show several patterns:

- in some cores there is a lack of continuity in, but not the complete disappearance of pollen down profile for the majority of wetland plant species (*e.g.*, wetlands 161, 162 and 163 in Fig. 5);
- there are fluctuations in pollen species which are present throughout the profile (*e.g.*, *C asiatica* and *S. virginicus* in wetland 161 in Fig. 5; *M. rhaphiophylla* in wetland 135 in Fig. 5);
- there is a lack of correlation in timing of the peaks in pollen numbers between separate basins (*e.g.*, *M. teretifolia*, *M. rhaphiophylla* and *M. cuticularis* in wetlands 161, 162, 163, 135 and 9–14 in Fig. 5);
- the total composition of wetland pollen from wetland to wetland at the same isochron level varies;
- the total composition of wetland pollen at different ages within the same wetland varies; for example, in wetland 161, the 1000 year old horizon is dominated by *C. asiatica* and *S. virginicus*, the 2000 year old horizon is dominated by *C. asiatica*, *S. virginicus*, *M. viminea*, *M. rhaphiophylla* and *M. teretifolia*, the 3000 year old horizon is dominated by *C. asiatica*, *S. virginicus* and *B. articulata*, and the 4000 year old



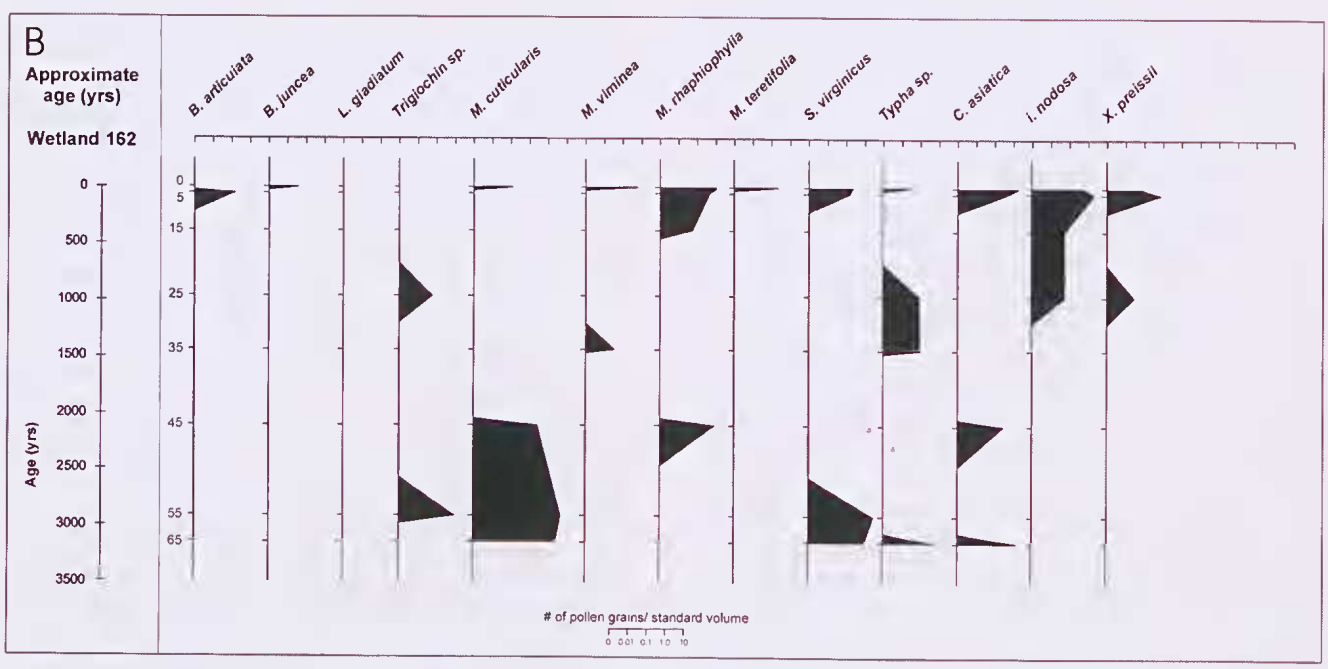
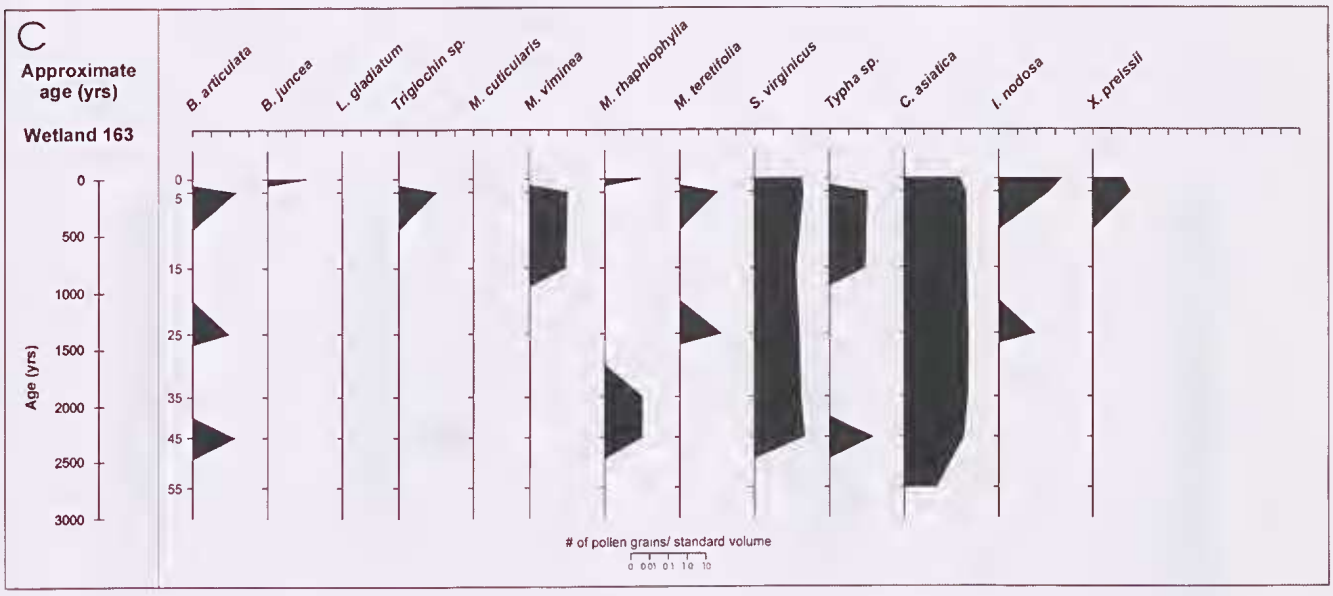
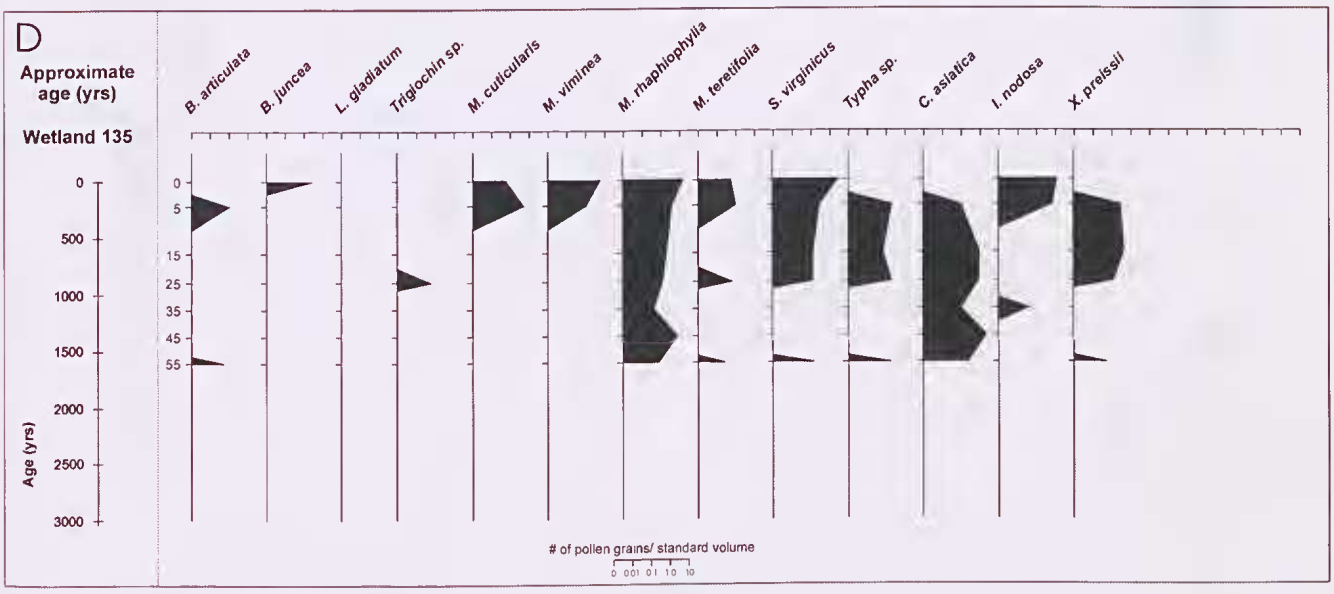


Figure 6. Graphs showing the composition of the various species of wetland pollen down the stratigraphic profile for each of the wetlands 161, 162, 163, 135, and 9–14, with the data on a chronometrically adjusted scale. The scale for pollen numbers is logarithmic.





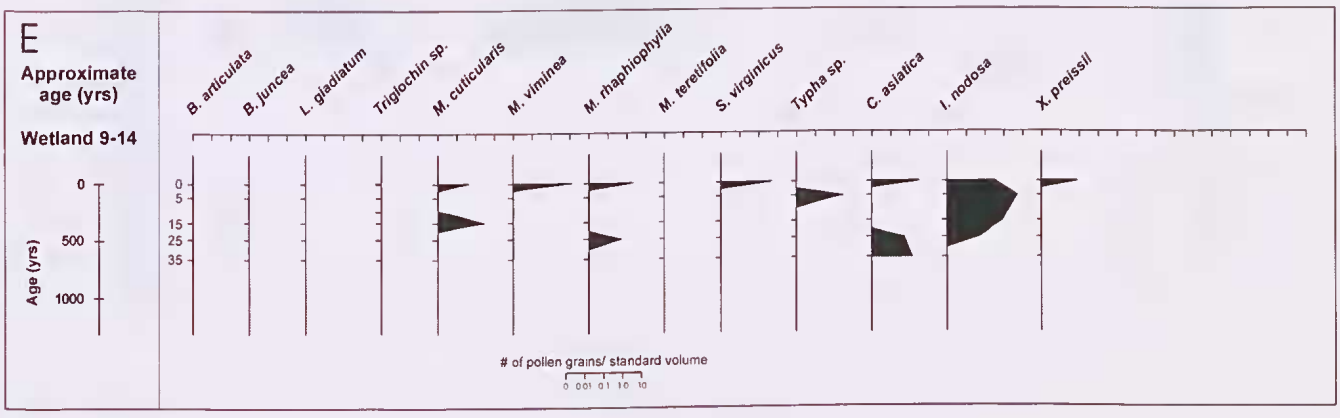


Figure 6 (cont.)

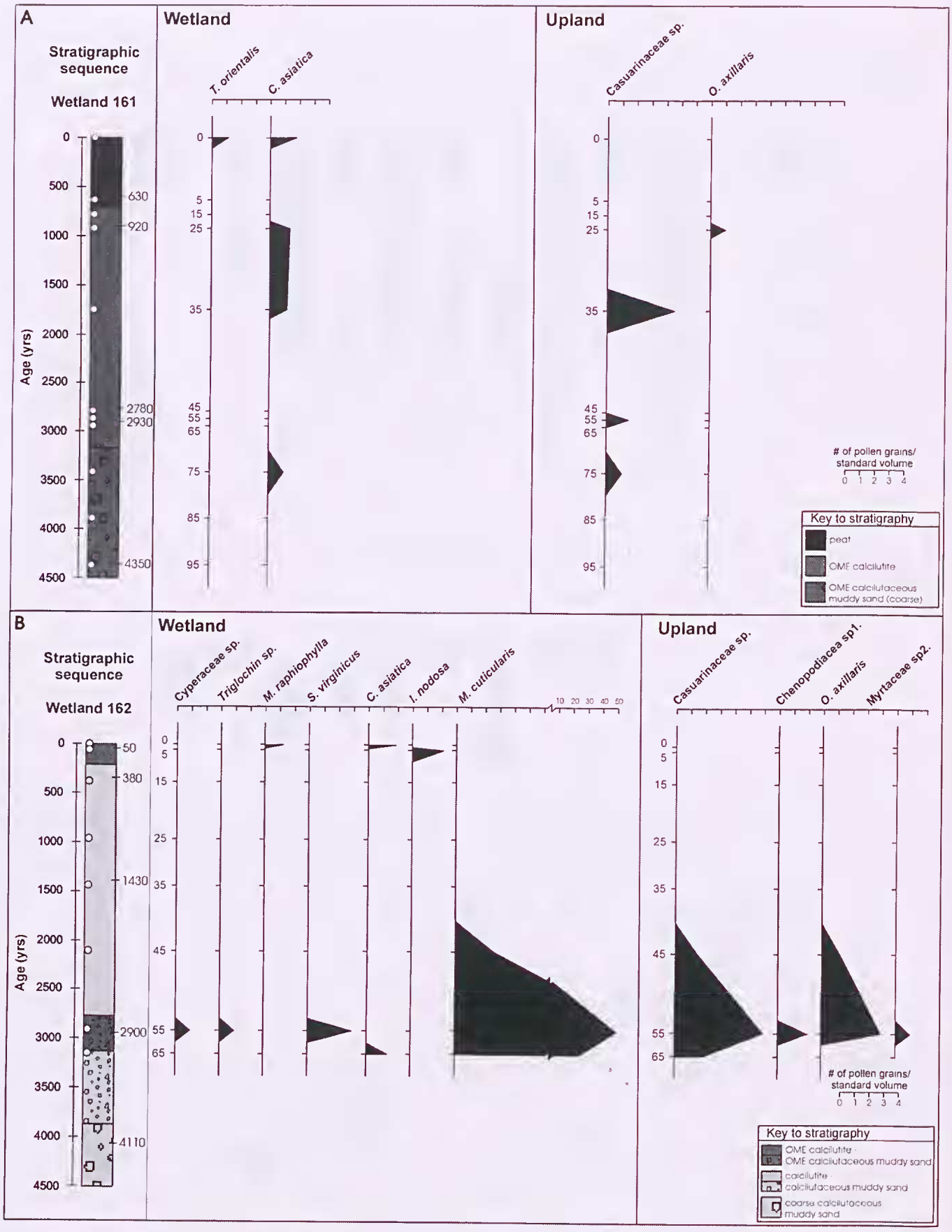


Figure 7. Graphs showing the composition of the most abundant species of wetland pollen and upland pollen down the stratigraphic profile for each of the wetlands 161, 162, 163, 135, and 9–14, with the data on a chronometrically adjusted scale. The scale for pollen numbers is logarithmic, with only pollen abundance > 10^3 noted on the graph.

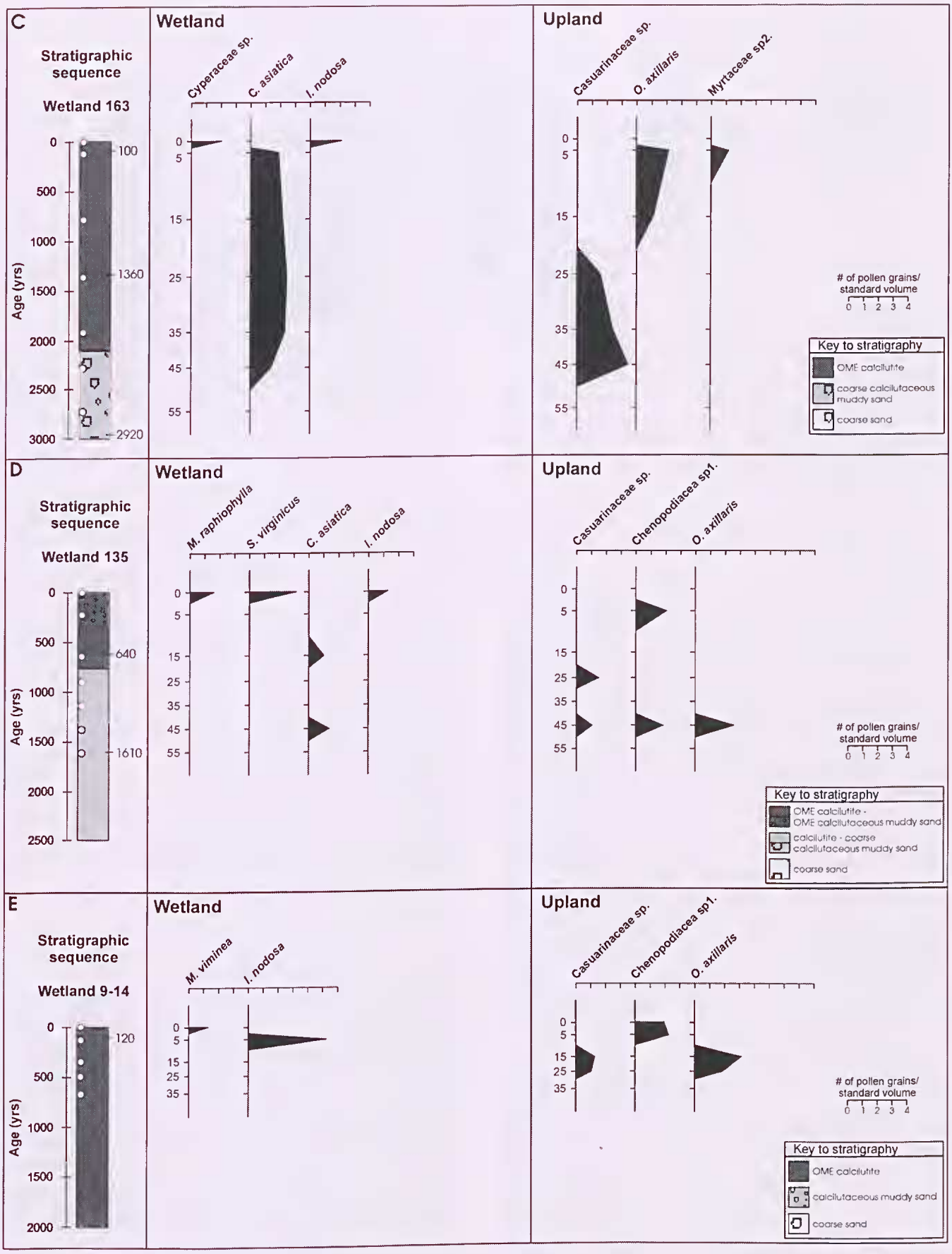


Figure 7 (cont.)

horizon is dominated by *C. asiatica, S. virginicus, M. rhaphiophylla* and *B. articulata*;

- there is an association of pollen species with sediment types;
- there are increases and decreases of marginal pollen in the down profile composition (*e.g., S. virginicus, I. nodosa, L. gladiatum*, and *M. viminea* in wetlands 161, 162, 163, 135 and 9–14 in Fig. 5);
- the appearance of *I. nodosa* and *X. preissii* (*i.e.*, within the last *circa* 1500 years) is recent; and
- in subsequent development, the presence and absence of species becomes more variable in the wetlands.

The patterns of pollen derived from wetland vegetation in individual wetlands, listed above, suggest that the ancestral distribution and abundance of plant assemblages in the Becher wetlands was, and continues to be, a function of intra-basin environmental changes caused by wetland evolution (C A Semeniuk 2006). *Centella asiatica* provides specific evidence for this conclusion: firstly, there is waxing and waning of its pollen throughout the profiles; secondly, although it occurs in the early stages of wetland development in all five wetlands, it is associated with different species.

Intra-wetland changes are likely to include responses to alternating periods of above and below average rainfall resulting in the expansion and contraction of assemblages and invasion of wetland marginal species observed during this study. The evidence from the fluctuations in the pollen of marginal plant species is that wetter and drier cycles occur much more frequently than is suggested by the other categories of pollen. These fluctuations are related to real presence and absence of a particular species in the wetland basin itself as it migrates between the wetland centre and the margin in response to water availability. The regularity of these pollen peaks suggests that there is a cyclicity in the amount of rainfall which recharges the wetlands.

Accompanying these wetter and drier cycles would be changes in wind patterns (wind strength and directions), which could account for fluctuations in abundance of imported wetland pollen species within a given wetland basin. The patterns of wetland pollen abundance down profile within an isochron framework, in combination with the patterns of abundance of upland pollen as a surrogate of wind contribution, show the variable nature of the pollen record from wetland to wetland as well as the variable contribution of upland pollen by wind even in adjacent wetlands. The results underscore the complexity of the pollen record.

Examining the range of pollen species from wetland plants occurring in sediments of similar age shows that species may or may not be present in the various wetland basins at the same time, and that in most cases the abundance varies even when the composition is similar. Given that the wetland plant species pool has been consistent over the last 4500 years, differentiation between one or two plants and an assemblage is important. Plants growing in association can be interpreted with respect to hydrological and hydrochemical changes based on the environmental attributes of their current habitats (C A Semeniuk 2006). For instance, an assemblage of *B. articulata* and *C. asiatica* indicates seasonal shallow inundation and fresh water, and an assemblage of *M. rhaphiophylla* and *C. asiatica*, or *M. teretifolia* or *M. viminea*, indicates seasonal waterlogging and hyposaline conditions, and possibly an expansion of species inhabiting the marginal zone, and the occurrence of *C. asiatica* and *S. virginicus* together indicates short term changes between seasonal waterlogging and dry periods. The occurrences of a single pollen type (*e.g., M. cuticularis, C. asiatica*, and *I. nodosa*) suggest dominance within the wetland rather than pure stands. Environmental conditions associated with the occurrences of these species are as follows: *M. cuticularis* indicates either less frequent waterlogging or more saline conditions, while *C. asiatica* and *I. nodosa* indicate freshwater, seasonal wetness, and an expansion of marginal wetland species in a basin.

In contrast to pollen from wetland taxa, that derived from upland vegetation exhibits continuity down profile, but with fluctuations in abundance. This suggests that delivery of upland pollen largely has been consistent, and being exogenic it has not reflected (hydrochemical, edaphic or hydroperiod) environmental conditions within the wetlands (that of course would influence wetland vegetation composition). However, the fluctuations in abundance of upland species cannot be correlated between the separate wetland basins. Peaks in pollen numbers can be consistently related to pollen from the same families or species, and in the case of three pollen types, to specific wind directions. This heterogeneity at given isochrons from wetland to wetland corroborates the results of Semeniuk *et al.* (2006) who showed that there was a heterogeneous distribution of exogenic pollen in the surface sediments of the Becher wetland basins.

Figure 8 presents upland pollen data down the stratigraphic profile in two formats: one as numbers of total upland pollen, and the other as the proportion of the three key species contributing to that total pollen number. While total upland pollen decreased between 2000 and 500 ^{14}C yrs BP in wetland 162, the proportion of Casuarinaceae pollen increased at that time, and while there was a peak in upland pollen in wetland 135 *circa* 1400 ^{14}C yrs BP, the proportion of Casuarinaceae pollen contributing to the total pollen count decreased at that time. In terms of interpreting the history of wind patterns that delivered the regional upland pollen to a given wetland basin, the graphs showing the proportions of contributing species are a better index of wind direction, while those illustrating total upland pollen numbers are a better index of wind intensity. *Circa* 2900 ^{14}C yrs BP, the numbers of Casuarinaceae and *E. marginata* pollen increased in wetlands 161 and 162, suggesting that this period was associated with prevailing easterly winds. High numbers of pollen from Chenopodiaceae (probably *Rhagodia baccata*, a beachridge species) in wetland 162 at the same time, could be interpreted as a change to more open conditions within the wetland basin, and increases in the pollen of wetland species (*M. cuticularis, S. virginicus* and *Triglochin* sp.) between 3100 and 2900 ^{14}C yrs BP suggest increases in salt tolerant plants. The sediment accumulating during this period was carbonate mud, a depositional product associated with sub-regional groundwater rise (due to coastal progradation) rather than increased rainfall. In combination, these factors

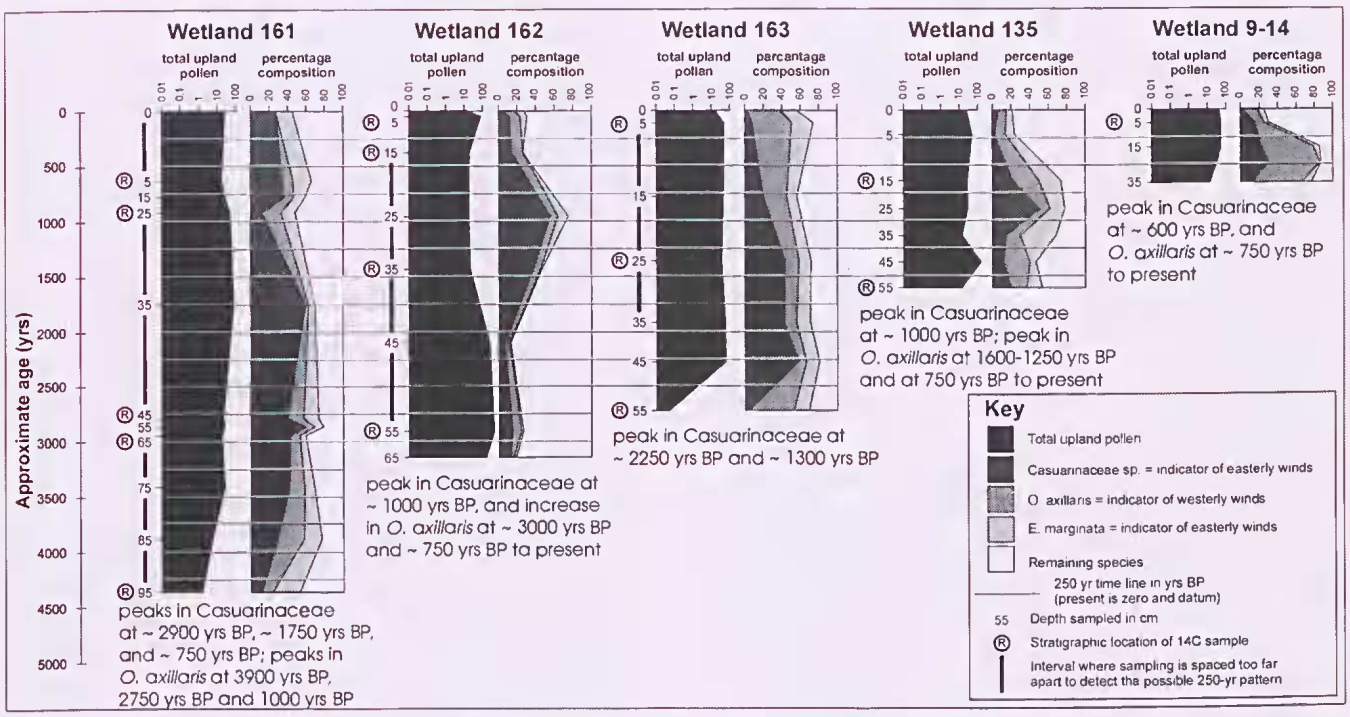


Figure 8. Graphs showing the composition of the three most abundant species of regional pollen down profile for each of the wetlands 161, 162, 163, 135, and 9–14, with the data on a chronometrically adjusted scale. The horizontal lines represent 500 year isochrons. The scale for pollen numbers is logarithmic.

suggest a wetland habitat adapting to drier climatic conditions. A similar increase in pollen from upland species in wetland 135 *circa* 1400 ^{14}C yrs BP may also indicate a period during which vegetation cover in this basin was more open, again, coinciding with carbonate mud deposition. However, supporting evidence cannot be obtained from wetlands 161 and 9–14 because there were no samples for this period, and in wetlands 162 and 163, although there are increases in the pollen of marginal wetland species (*M. viminea*, *I. nodosa*), and a decrease in *C. asiatica*, the composition of the wetland pollen does not suggest a sudden and intense change comparable to the arrival of *M. cuticularis* in the earlier period.

Discussion and conclusions

Whether pollen of wetland vegetation is *in situ*, derived from the wetland margins (signalling comparatively drier phases in the history of the wetlands), or transported by wind to a particular basin from other proximal or distal basins, is a critical consideration in reconstructing wetland vegetation history from the pollen record. Pollen rain and *in situ* pollen contribution, as preserved in the surface sediments of the Becher wetlands, was shown by C A Semeniuk *et al* (2006) to be heterogeneous, and the implications are that while exogenic pollen transported from distal sources preserved in the stratigraphic profile may reflect the long-term regional and sub-regional species pool, it cannot be used to reconstruct comparative vegetation history of individual wetlands. Difficulties in interpretation of the pollen record also will arise for wetland taxa when the occurrence of a given species is the result of *in situ* production *and* wind transport.

Interpreting any fossil pollen record or even its contemporary record is complex (Luly 1997), as it is influenced by the relative rates of pollen production, taphonomic considerations, vectors of transport, and in regard to aeolian transport, wind directions and wind speeds in relation to flowering times, and also whether the various flowering plant species of the vegetation assemblages are maintaining their populations sexually or asexually. A full analysis of these factors in generating a fossil or contemporary record was beyond the scope of this study.

In addition, there are other factors contributing to the difficulty in interpreting the vegetation history of each specific pollen sequence in the Becher wetlands. For instance, if the vegetation changes in its fundamental composition relatively quickly in relation to, say, 20-year and 250-year climatic fluctuations, or hydrochemical changes in local groundwater, then to detect such changes the pollen sequences within the rates of sedimentation determined by ^{14}C dating need to have been sampled on a *circa* 1 mm interval. Monitoring of vegetation over the 10 years of study by C A Semeniuk (2006) in this area indicates that many species indeed fluctuate in abundance in response to short term climatic variations. On the other hand, bioturbation, which is prevalent in the wetland sediments of the Becher Suite, locally mixes substrates over at least a 10 cm interval, obliterating any potential fine scale sequencing of pollen. This means the pollen record from the sampling interval potentially records mixed wet and dry climate assemblages that may have alternated on a 20-year or 250-year turnaround. Even the surface pollen record from the wetlands may not be reflecting the extant assemblage compositions, but rather, given the accretion rates of sedimentary material within the wetlands, and

bioturbation, a composite of up to several hundred years of record (*e.g.*, wetland 161).

Also, the relative abundance of pollen in the stratigraphic record may not reflect relative abundance of plant cover. Without autoecological and taphonomic information on the relative production rates and preservation of pollen from the various species, and the relative importance of flowering and seed production as a population maintenance strategy compared to clonal growth, the pollen record must be used with caution to interpret former relative proportions of species that contributed to the stratigraphic record. Further, without rigorous studies on the modern dispersion rates and dispersion patterns (involving identification of major wind flow paths, consistently generated eddies, and grain size fallout zones), it is not clear how far the pollen of a given species can be transported by wind and water. This means that it is difficult to determine exactly what are wholly intra-basinal contributions *versus* margin contributions *versus* possible extra-basinal contributions. The discrimination of wind transported pollen from pollen generated within the basin, in response to a medium term climate change to more arid conditions, is hampered by the fact that the species abundances and composition are likely to be the same in either situation. In addition, in the Becher wetlands, the species which are adapted to groundwater salinity are also the species that have efficient pollen dispersal mechanisms. As mentioned earlier, some of the patterns of down-profile abundances for wetland species appear to mirror patterns of abundances of upland species delivered to the wetland basin through the agency of wind (Figures 5 & 7). Yet, if increased wind activity was associated with a medium term climate change from relatively humid to more arid conditions and a concomitant increase in wetland groundwater salinity, the change in plant associations to more saline tolerant species could produce a similar pollen abundance pattern. For example, the occurrence of pollen of *Melaleuca cuticularis* and *Sporobolus virginicus* within a wetland either may signal widespread transport into a given wetland basin, or reflect the response of these species to local conditions of medium term increased groundwater salinity. This consequence is an important consideration in reconstructing the history of wetland vegetation within a particular basin.

Lastly, a major limitation to pollen studies in the Becher wetlands is the lack of finely spaced dated material. While there have been a large number of ^{14}C dates determined in the area, in terms of sedimentary sequence, and for dating the base of the sequences, there are not enough dates to be able to correlate isochronous events across the various wetland basins. For example, while there is a marked pollen event in wetland 162, with an abundance of *M. cuticularis* and *S. virginicus* at approximately ^{14}C age of 2900 yrs BP, the exact equivalent ^{14}C age interval to a precision of say, 250 years, has not been sampled in the other wetlands because of the sampling interval selected. Therefore a given pollen event in one wetland cannot and has not been correlated across to the other wetlands.

With these caveats, and awareness of the limitations described above, there are several conclusions that can be made from this pollen study about the vegetation history. The pollen record indicates that the species pool of wetland plants colonising the Becher Suite wetlands has remained fairly stable over the last 4500 years. Both the sediments and the pollen indicate that the history of the wetlands included alternate wetter and drier periods. As these periods progressed, the species adapted to one or other of the phases came into dominance and then decreased in abundance. Overall, many of the wetland plants which are tolerant of periodic higher water salinity and changes in water periodicity continually adapted to the annual cycle of wet and dry. Over longer term climate cycles, the areas within the wetland basin under any one assemblage may contract and expand, with the prevailing hydrological and sedimentological conditions determining the composition of the vegetation. During the course of the study, the wetlands of the Becher Point region experienced a transition from relatively wet to dry to a beginning of a return to wet conditions as part of the 20-year cycle, and while there were changes in plant assemblages, the major assemblages, floristically and structurally, remained essentially the same. For example, wetland 161 remained dominated by *B. articulata*, wetland 162 remained dominated by *M. teretifolia* closed scrub, wetland 163 remained dominated by *J. kraussii*, and wetland 135 remained dominated by low forest of *M. rhaphiophylla*. The 20-year climatic patterns may not effect enough change in vegetation to be detected in the pollen record.

Wetland plants are more likely to respond to intra-wetland environmental changes than regional changes, given that the factors which determine their distribution are small scale such as geohydrology, sediment chemistry and hydrochemistry (C A Semeniuk 2006), and that the species pool of wetland plants in the Becher Point area occurs throughout the entire southwest region of Western Australia, spanning humid to semi-arid climatic zones. Other studies corroborate the findings herein that changes in wetland vegetation, particularly in seasonally inundated or waterlogged wetlands, are related to the localised fluctuations in the hydrological regime (Boyd 1990; Jenkins & Kershaw 1997). The exception to this general pattern has been the comparatively recent arrival of *X. preissii* and *I. nodosa* indicated by the occurrence of their pollen *circa* 1500 ^{14}C yrs BP. As the pollen is first recorded in each of the wetland cores around this time, and one or other of the species continues to occur in the record up to the present, it suggests a response to progressively wetter climate.

Occurrences of upland pollen taxa, in the stratigraphic (geohistorical) record, whether from regional or local ridge sources, are also variable from basin to basin. Peaks in upland pollen abundance sometimes coincide, as in wetland 162 and 135, but often do not, even when the pollen is being transported from the same source and in the same direction, *e.g.*, *E marginata* and Casuarinaceae pollen in wetland 163 (Fig. 8). The most reliable isochronous interface in the Becher wetlands in fact is the modern surface, but here the distribution of three diagnostic upland pollen species subregionally is heterogeneous, leading C A Semeniuk *et al.* (2006) to conclude that there is no definitive pattern of distribution in upland pollen with respect to the present climatic conditions.

Use of upland pollen as a direct indicator of wind

activity in a correlative manner also has several problems. While it is clear that such pollen, where abundant, would have to be delivered to a wetland basin by wind, detailed examination of the composition of upland pollen shows variability, with different species contributing at different geohistorical times. For instance, at various times, for a given wetland basin, there is contribution from species that are located to the east of the wetlands, reflecting easterly wind dominated delivery, and there is contribution of species that are located nearer the coast, reflecting westerly wind delivery. While there may be differential spatial deposition of upland pollen in response to different wind fields and topography, it cannot even be assumed that the temporal variable deposition of the pollen within the *same* basin will reflect changes in wind patterns and hence some climate control. Further, wind patterns can be complex, and can vary in direction and strength from year to year, even within a regionally consistent climate, such that differential delivery of regional pollen taxa over time, in terms of composition and abundance, may not be signalling climate changes but rather the complexities of the aeolian processes. Also, any medium term climate changes that involved modest shifts in wind direction and speeds, as governed by oceanic and/or interior arid hinterland effects, may not have been ubiquitous across the region or sub-region. Local topography of higher than normal beachridges, or of continuous swales acting like funnels, may have influenced local deposition. Prominent marginal vegetation may have acted as interceptors to transported pollen in contrast to open basins with no barriers. In regard to dispersal of pollen of wetland species, the occurrences of upland pollen species within the wetland were used as coarse indicators of local wind and its possible contribution as a vector to deliver pollen of wetland species to a given wetland, *i.e.*, the wind that delivered upland pollen to a given wetland may also have delivered pollen from wetland species elsewhere.

Any palaeo-climatic reconstruction based on pollen from upland vegetation is further complicated by the fact that the species pool encountered on the ridges of the Becher Cuspate Foreland is similar to coastal ridge and dune vegetation between Augusta and Jurien Bay, an area which encompasses humid to semi-arid climates (Gentilli 1972), even a major climate change from humid to semi-arid, *i.e.*, a change in rainfall from 900 to < 500 mm per annum, may not be deduced from palynological investigations from coastal regions and coastal flora. A similar problem has been encountered by several palynologists (Boyd 1990; Newsome & Pickett 1993). In a study of Myrtaceae pollen in southwestern Australia, Newsome & Pickett (1993) noted that the region is dominated by sclerophyll plant communities, whose high floristic diversity is related to edaphic rather than climatic variability, and that *Eucalyptus* is widespread both as dominant and sub-dominant species within the forests and woodlands of different climatic zones.

The most reliable information on climate variability from the pollen record is provided by the marginal vegetation, firstly, because the pollen is derived from *in situ* basin vegetation, and secondly, because vegetation at the wetland margin is the most responsive to changes in water availability, increasing in cover abundance in response to drier conditions and retreating under wetter conditions. In the Becher Point area, the pollen record of marginal vegetation shows that more regular and more closely spaced changes in rainfall have occurred than have been postulated in previous Western Australian studies.

The record of pollen in the Becher Point area only spans the past 4500 years, and so does not encompass the climate patterns over the whole of the Holocene. The changes in species abundances are commensurate with the long term change in climate from relatively dry to wetter conditions, but definitive indicators of climatic change are confounded by short and medium term changes in pollen composition and abundance. The palaeo plant assemblages, reconstructed on the analyses of pollen from wetlands and ridges of the Becher Cuspate Foreland, suggest both intra-basinal responses and climatic factors are the driving mechanisms for short and medium term vegetation changes. However, these responses, such as areal contraction and expansion, and changing dominance within an assemblage which also typify annual and short term inter-annual rainfall fluctuations, are highly individualistic.

To date, in Western Australia, there have been no published studies directed towards determining the heterogeneity of the pollen record in the large isolated wetland basins, even though studies elsewhere have indicated the complexities inherent in the accumulation of pollen (Dodson 1983; D'Costa & Kershaw 1997; Luly 1997). Equally, while there have been palynological analyses of single cores in basin wetlands in Western Australia, spanning localities from Boggy Lake (near Walpole), and Perth, to Rottnest Island (Churchill 1968; Backhouse 1993; Newsome & Picket 1993), there has not been an exploration of how representative the pollen records of these basins are of the region or subregion. C A Semeniuk *et al.* (2006) concluded that there is difficulty in interpreting regional climate patterns from the pollen record using surface pollen, because of heterogeneous and complex delivery of exogenic pollen, and in short term (temporal) variation in plant assemblages, respectively. Such heterogeneity and complexity is to be expected in the stratigraphic record. For example, using exogenic, distally derived upland pollen species, the stratigraphic variation in abundance of *Eucalyptus* and *Casuarina* in time and in different basins indicates that the isochronous influx was heterogeneous, confirming conclusions of C A Semeniuk *et al* 2006. Further, isolated single cores can lead to misleading interpretations in relation to climate changes. For example, the marked fluctuations of some key wetland species such as *Melaleuca cuticularis*, if viewed only from a single core, would imply climate changes, but multiple cores in the areas contradict this. *Melaleuca cuticularis*, rather increases and decreases in abundance as the wetland basin hydrochemically and hydrologically evolves or fluctuates. Essentially, while there are distinct small basins in Becher Point area, each wetland has had a different vegetation history. In larger basins, in areas elsewhere from Becher Point, variable vegetation (pollen) history would be manifest across concentriform, maculiform, gradiform and heteroform wetland assemblages (C A Semeniuk *et al.* 1990), particularly if they were dynamic, or in heterogeneous and dynamic

vegetated wetland margins particularly with bacataform organisation. The results from such settings would be a wetland basin filling with sediment with a heterogeneous influx of locally derived pollen types (Luly 1997), and not necessarily reflecting climate history. In this context, C A Semeniuk (2006) concluded that single basin palynological history in the Becher Point area, with lithologic changes, more likely reflects intra-basin evolution (*i.e.*, stratigraphic evolution to develop hydrochemical; evolution, and then serial vegetation responses), than regional climate history.

On the other hand, there is some evidence for climate changes in the Becher Point stratigraphic record, palynologically (as noted above) and sedimentologically. The appearance of *Isolepis nodosa* and *Xanthorrhoea preissii* at *circa* 1500 ^{14}C years BP occurs in all the wetland basins studied, and would imply that their incursion into wetland margins on the beachridge plain (regardless of the individual vegetation history of a wetland basin to that point) was broadly synchronous in the Becher Point region, implicating a climate change. The corroborative sedimentary evidence for such a climate change is the subject of another study.

In summary, in relation to climate, a combination of palynological and stratigraphic data, essentially independently corroborative information, within the *same* basin, indicating the same direction of change in environmental factors, may be used to pinpoint changes in climatic conditions. In the Becher area, examples of such changes occurred approximately 3000–2900 and 1500 ^{14}C yrs BP.

With the abundance of radiometric dates in this study area, C A Semeniuk (2006) showed that the sedimentation rates in the various wetland basins were variable. As a result, when the stratigraphic profiles are adjusted to broadly represent equal-age increments, there is internal distortion of the thickness of the sediments between any two 1000-year isochrons. This would mirror variable rates of sedimentation. The implications, however, are that to rigorously construct a climate history from cores, there needs to be enough radiometric dating to circumvent the variable sedimentation rates which would in turn affect the relative abundance of pollen, *i.e.*, the pollen record needs to be assessed within a context of rapidly accumulating *versus* condensed sequences.

Acknowledgments: This paper derives from the R&D endeavour of the V & C Semeniuk Research Group, registered as VCSRG Research Project # 3 with AusIndustry in Canberra, ACT.

References

Backhouse J 1993 Holocene vegetation and climate record from Barker Swamp, Rottnest Island, Western Australia. Journal of the Royal Society of Western Australia 76: 53–61

Boyd W E 1990 Quaternary pollen analysis in the arid zone of Australia: Dalhousie Springs, Central Australia. Reviews of Palaeobotany and Palynology 64: 331–341.

Churchill D M 1968 The distribution and prehistory of *Eucalyptus diversicolour* F. Muell. *E. marginata* Donn ex Sm and *E. calophylla* R Br in relation to rainfall. Australian Journal of Botany 16: 125–151.

D'Costa D & Kershaw A P 1997 An expanded recent pollen database from south-eastern and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45: 583–605.

Dodson J 1982/1983 Modern pollen rain in southeastern New South Wales, Australia. Review of Palaeobotany and Palynology 38: 249–268.

Erdtman G 1960 The acetolysis method: a revised description. Svensk Botanisk Tidskrift 54: 561–564.

Gentilli J 1972 *Australian Climate Patterns.* Melbourne: Nelson

Jenkins M A & Kershaw A P 1997 A mid-late Holocene vegetation record from an interdunal swamp Mornington Peninsula, Victoria. Proceedings of the Royal Society of Victoria 1092: 133–148.

Lloyd P J & Kershaw A P 1997 Late Quaternary vegetation and early Holocene quantitative climate estimates from Morwell Swamp, Latrobe Valley, south-eastern Australia. Australian Journal of Botany 45: 549–563.

Luly J G 1997 Modern pollen dynamics and surficial sedimentary processes at Lake Tyrrel, semi-arid north-western Victoria, Australia. Review of Palaeobotany and Palynology 97: 301–308.

McKenzie G M & Kershaw A P 1997 A vegetation history and quantitative estimate of Holocene climate from Chapple Vale, in the Otway region of Victoria, Australia. Australian Journal of Botany 45: 565–581.

Newsome J C & Pickett E J 1993 Palynology and palaeoclimate implications of two Holocene sequences from south-western Australia. Palaeogeography Palaeoclimatology Palaeoecology 101: 245–261.

Nilsson S & Praglowski J 1992 *Erdtman's Handbook of Palynology* 2nd edition. Copenhagen: Munksgaard

Phipps D & Playford G 1984 *Laboratory techniques for extraction of palynomorphs from sediments.* Department of Geology, University of Queensland No. 11 1–23.

Searle D J, Semeniuk V & Woods P J 1988 Geomorphology, stratigraphy and Holocene history of the Rockingham-Becher Plain, South-western Australia. Journal of the Royal Society of Western Australia 70: 89–109

Semeniuk C A 2006 The Becher Wetlands – a Ramsar site: A case study of the evolution of wetland habitats and vegetation associations on a Holocene coastal plain, south-western Australia (Springer, Netherlands)

Semeniuk C A, Milne L A, Ladd P & Semeniuk V 2006 Pollen in the surface sediments of wetlands in the Becher Point area, southwestern Australia: a baseline for use in interpreting Holocene sequences. Journal of the Royal Society of Western Australia 89: 27–43.

Semeniuk C A, Semeniuk V, Cresswell I D, & Marchant N D 1990: Wetlands of the Darling System, southwestern Australia: a descriptive classification using vegetation pattern and form. Journal of the Royal Society of Western Australia 72: 109–121

Semeniuk V & Glassford D K 1989 Bassendean and Spearwood Dunes: their geomorphology, soils and stratigraphy as a basis for habitats of *Banksia* woodlands. Journal of the Royal Society of Western Australia 71: 87–88.

Semeniuk V & Semeniuk C A 2004 Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part 1: sediment particles, typical sediments, and classification of depositional systems.. Journal of the Royal Society of Western Australia 87: 139–186.

Semeniuk V & Semeniuk C A 2006 Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part 2: distribution of sediment types and stratigraphy. Journal of the Royal Society of Western Australia (in press)

V & C Semeniuk Research Group (1991) *Wetlands of the City of Rockingham: their classification, significance and management.* Report to City of Rockingham and Heritage Council of Western Australia Perth, Western Australia.